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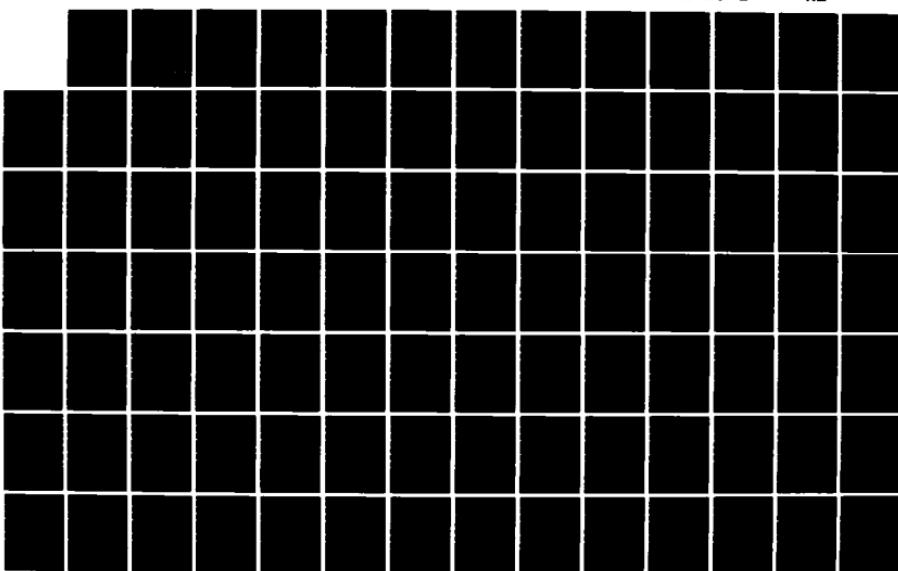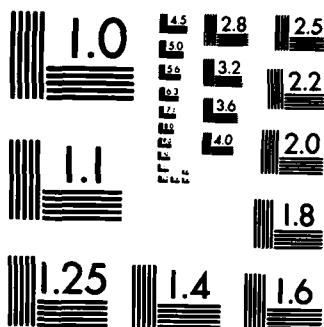
MICROCOPY RESOLUTION TEST CHART

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CR 85.010

NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

Sponsored by
NAVY ENERGY RDT&E OFFICE (ONT-07E)
NAVAL FACILITIES ENGINEERING COMMAND

LIGHTING CONTROL SYSTEMS HANDBOOK

June 1985

An Investigation Conducted by:
Smith, Hinchman & Grylls Associates, Inc.
455 West Fort Street
Detroit, MI 48226

N68305-9213-7980

85

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
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20 ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

The functional components of a lighting control system are described using a modular approach. The interaction of the components and the specific kind of hardware available for each function are detailed. The components are then combined into various control systems beginning with simple manual control and concluding with closed loop automatic control.

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Emphasis is placed on energy and economics.

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1.   INTRODUCTION

1. INTRODUCTION

1.1 HANDBOOK PURPOSE AND PHILOSOPHY

As the world's population continues to grow, energy consumption generally grows with it. The use of new materials has made many of our production methods more energy intensive then they ever were. There is conflicting opinion about how long our fossil resources will last, but that supply is limited and the cost of supplying the energy is ever increasing. With no intent to enter the controversy on the merits of nuclear energy, the above comments on the increased costs of fossil fuels are generally true and will continue to be true with respect to energy in general until a major breakthrough that is acceptable to mankind occurs in the production of energy.

Due to limited resources and energy costs that increase at a rate that is faster than inflation, emphasis has been placed on utilizing energy more effectively. From a national point of view, there is a desire to be less dependent upon foreign sources. From a commercial point of view, it makes good business sense to save energy if the return on investment is better than another investment that could be made with the same monies.

Attention is focused on lighting controls in buildings as one means to reduce energy consumption. System performance needs to be improved, if not optimized, without sacrificing the quality and quantity of light required to perform specific visual tasks. With advancing technology, many new lamps, ballasts, sensors, and control devices are constantly entering the market. The improvements in these "tools" challenges the control system designer to use them in the best, most cost beneficial manner to reduce energy consumption. This challenge applies to both new building design as well as to retrofit energy conservation projects. Both building types require the same philosophy in the design of a lighting control system. The designer aims to control light, supplying it only when and where a need exists and only in the quantity necessary.

This Handbook covers the functional components of a lighting control system in a building block approach. How the components interact and specific hardware available for each of the functions is described. The components are then put together into various control systems beginning with simple manual control and concluding with closed loop automatic control systems. The Handbook describes energy costs and a method of evaluating utility cost savings. Finally, examples describe some typical control applications as well as the savings associated with the use of controls.

1.2   CONTROLS PLANNING

There are two approaches a designer may follow in planning a control system:

- Design the control system after completion of the lighting system, or

- Design the control system simultaneously with the design of the lighting system.

For an existing installation, only the first approach applies. For a new or remodeling installation, either method will accomplish the design goals, but the second is preferred. A lighting designer who keeps in mind how the control system will be used may vary the type of fixture, the location of a fixture, the number of fixtures, the type of lamp, or the number of lamps. This, in turn, will vary energy consumption and system cost, both initial and operating.

Initially, the control system designer must collect information and then study and weigh several areas including:

- Operational schedule of the building/space.

- Size of the space and the number of people in each space.

- Flexibility of the room layout.

- Budget of the project.

- Specific functions of each space.

- Available daylight.

- Maintenance/cleaning schedule for lamps and fixtures.

- Code requirements.

- Illuminance, luminance, and other applicable visibility criteria.

- Power utility rates.

- Other building systems (HVAC, etc.).

By understanding and integrating this information, the designer will be in position to evaluate alternative control schemes for each lighting system. For most lighting systems, the saving of electrical energy and its resultant cost are the principal reasons for the implementation of a control system.

Only by acquiring the above knowledge can convenient and cost effective control systems be developed.

It is important to note that a control system of significant complexity may be required strictly for the functional needs of a space. For example, conference rooms often require local switching and/or dimming of the lighting in order that projection systems can be used. In cases such as this, energy conservation can only be a side benefit of the controls. Nonetheless, the control system required by need must respond to the needs and economic limits established for it. Justification by energy savings is simply not required.

In planning for design of controls, special attention should be given to the project budget. There are two basic economic conditions facing the designer.

- The project has a fixed construction cost budget. Lighting controls, whether or not providing significant energy savings, must fall within the overall budgetary limits.

- The project is an investment, and design measures which provide for a minimum rate of return for the increment of investment over "conventional" approaches will be permitted.

These conditions provide the basis for design.

Planning of controls for energy conservation begins with a determination from the available information of whether the space is appropriate for energy conservation by means of control principles. Many space uses will prohibit the use of controls for conservation purposes, either due to need or due to code; e.g., emergency lighting requirements. Only those spaces which present a viable opportunity for conservation by control should be considered.

For each such space, the identification of zoning possibilities is important for proposing responsive schemes of control. A lighting control zone is a functional area that has common lighting requirements and common control opportunities. A zone will typically have a common occupancy and common tasks or at least common task requirements. The smallest control zone is a task as shown in Figure 1-1 and progressively increases in size to space, area, room, part floor, full floor.

For any large space, such as an office building floor, there may be many possible divisions of spaces into lighting control zones. From a control point of view, the smaller that the control zone is, the more precisely can it be controlled and, therefore, minimize the consumption of energy. It should be recognized that, usually, the smaller the zone, the

TASK

SPACE

AREA

ROOM

PART FLOOR

FLOOR
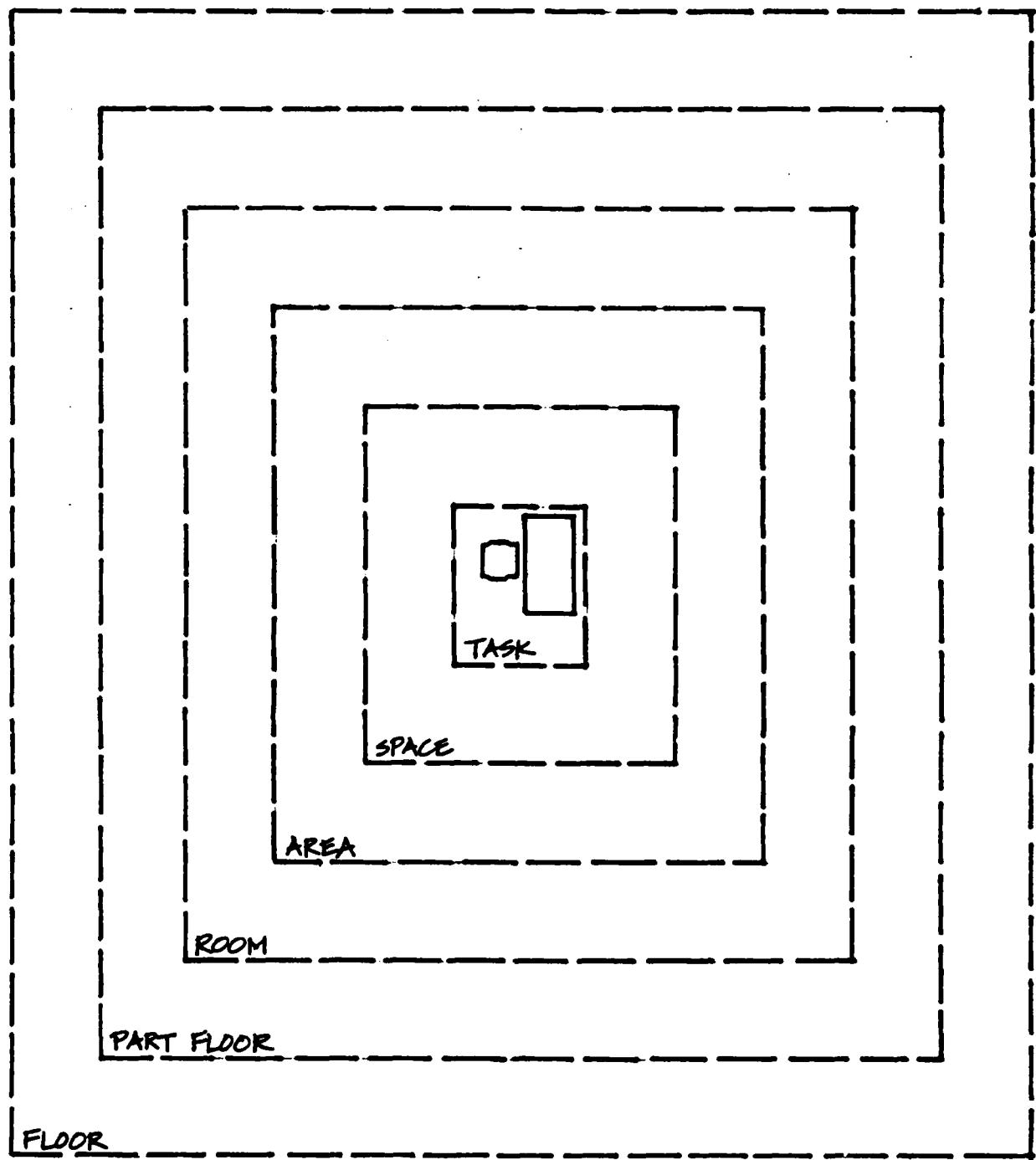
LIGHTING CONTROL ZONE
FIGURE 1.1

greater the initial cost for construction. This is true because there will be more equipment (sensors, switches, etc.) per square foot of space as well as more branch circuit wiring.

The next step is to evaluate each set of zonings for energy conservation potential. The evaluation should be based upon the following items:

- Size of control zones

- Time schedule of occupancy, tasks, and functions

- Frequency of occupancy, tasks, and functions

- Availability of daylight

- Maintenance schedule

- System energy and demand requirements

- Code requirements

- Desires for mood and effect

- Maximum available levels of illuminance/luminance

- Desired levels of illuminance/luminance

- Control system costs

- Impact on building systems

For each item, the potential impact of a control system on initial cost and both demand and energy charges should be considered.

Planning for control systems design is concluded by the identification of the electrical systems serving the lighting system. In most electrical power distribution systems, there will be locations at which blocks of lighting may be controlled ON or OFF; i.e., at feeders and branch circuits. The choice of which luminaires are combined onto a common branch circuit can have a profound influence on the options available for control and can itself result in a simple control system involving large zones. This is particularly true where daylighting influences only a portion of a space or where furniture divides a space into functionally separate zones.

1.3   DEFINITIONS

- Daylight   — light obtained from sunlight or the
                       brightness of the sky during the
                       day. Sometimes called "natural
                       light".

- Dim   — vary the intensity of an electric
                       lighting system. Analagous to
                       "fade".

- Electric Light   — light obtained from lamps of all
                       types that receive their energy
                       from electricity. Sometimes mis-
                       leadingly   called   "artificial
                       light" because electric light is
                       real.   The spectrum is usually
                       "unnatural" compared to daylight.

- Control Device   — the element in the system that
                       changes   the   input   to   the
                       controlled   element,   thereby
                       changing the illumination level.

- Controlled
  Element   — the element in the system, a lamp
                       or ballast, that results in pro-
                       ducing light output.

- Decision
  Element   — a logic function that relates the
                       need for illumination into   the
                       action required to achieve the
                       illumination.

- Sensor   — device that measures a physical
                       condition that can be interpreted
                       as meaning that there is a need
                       for illumination. It may measure
                       the actual level of illumination,
                       a function of time that represents
                       a need for illumination, or the
                       presence of individuals that need
                       illumination.

2. FUNDAMENTALS

2. FUNDAMENTALS

2.1 CONTROL SYSTEMS

2.1.1 General

A lighting control system is a combination of various components connected together in such a manner so as to permit the illumination in a space or zone to be controlled to some prescribed condition. Within the control system, there is a flow of electrical energy, a flow of light energy, and a flow of information. The various components are shown inter-connected in the block diagram of Figure 2-1 where the electrical, illumination and information flows are indicated. Each of the blocks exists in every control system and may be simple or complex, manual or automatic, individual or combined with other blocks.

The electrical energy is seen to flow from an outside source to the Control Device and then to the Controlled Element where electrical energy is converted to light energy. Illumination is produced by the proper location of light energy within a space. It is the Lighting System that converts this light energy into an efficient (usually) producer of illumination. The information flow is seen to be from the measurement of an existing physical condition in a Sensor through a Decision process to a Control Device that regulates the flow of electrical energy.

2.1.2 Lighting System

The "Lighting System" includes the luminaire, reflector, lens or diffuser and the physical location and orientation of the luminaire. The "Lighting System" design is beyond the scope of this Handbook and considers, as a basis, the desired illuminance, luminance, and other applicable visibility criteria, which may be single values, multiple values, or infinitely variable values. Other considerations include economic values, aesthetics, and functional, biological and psychological needs.

2.1.3 Sensor

The "Sensor" is a function that determines there is a need for illumination. In its simplest form, the function is performed by an individual who perceives the illumination requirements of the space. In its non-biological form, the "Sensor" may be a component that determines the actual illumination, the time of day, the passage of time, or the absence or presence of individuals in the space.
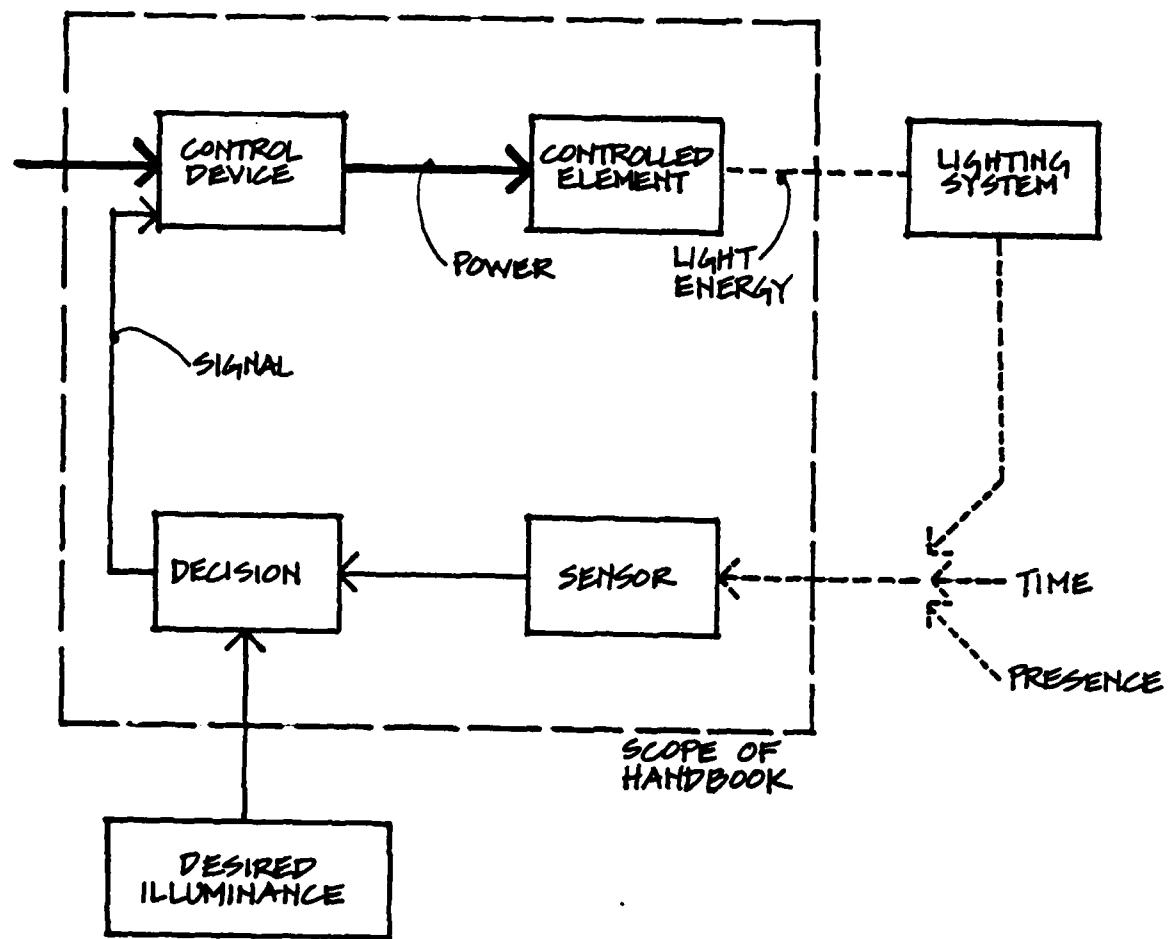
CONTROL SYSTEM BLOCK DIAGRAM
FIGURE 2.1

2.1.4 Decision Element

With the information obtained from the "Sensor", a "Decision" is made to adjust the "Lighting System" (or a part of it) to ON or OFF or dim. In the simplest form, the individual decides that it is too dark and that the lights should be turned ON in order to be able to see adequately. In its more complex form, a microprocessor might have Sensor inputs that sense the illumination level, the time of day, and the presence of individuals in the space and then provide an output that will change the illumination level.

2.1.5 Control Device

Changes in illumination level are accomplished by changes in voltage, either power level of signal level, to lighting equipment. The change in voltage may be from zero as one value, to rated voltage as a second value, or to some intermediate value. The "Control Device" is the element in the block diagram that changes the voltage. The input may be manual or automatic (electrical or mechanical), and the output may be discrete (single valued) or continuous. A manually operated toggle switch or circuit breaker is an example of a manual input and discrete output. A simple wall dimmer requires a manual input to position the input handle or knob and the output is a voltage value which varies with the manual setting of the knob. A relay or contactor is similar to a toggle switch in that the output is discrete (either ON or OFF), but the input is electrical permitting the device to be operated automatically. In a complex form, a remote solid-state dimmer has a low voltage variable input and gives a variable output voltage with sufficient current to drive the "Controlled Element".

2.1.6 Controlled Element

Changes in illumination are effected by changing the voltage to a lamp directly (as in an incandescent or quartz halogen lamp), or by changing the input to a ballast which in turn operates a discharge lamp (as in fluorescent, mercury vapor, metal halide, high or low pressure sodium lamps). The "Controlled Element", shown in the block diagram, is the lamp or ballast and is separately identified from the "Lighting System" (although a part of it) because the former may be varied while the latter cannot. Changes in the "Lighting System" are beyond the scope of this Handbook.

2.1.7 System Configuration

There are many possible combinations of the control blocks that can be used within the same building. Often the same electrical and light energy flow is used with various different information flows for control. Or conversely, a given information flow (sensing and decision) can be used

to control a Lighting System consisting of two different
Controlled Elements.

Considerable flexibility and innovativeness can be
achieved if it is recognized that the selection of control
components for the flow of information is often independent
of the electrical and light energy flow. Thus, a common
Lighting System with the same Controlled Element (ballast
and/or lamp) may be used throughout a building with different
controls used in each zone dependent upon the specific
lighting needs within each and every zone.

2.2 SENSORS

2.2.1 General

Determining the need for increased or decreased illumination is the function of the Sensor. In general, the Sensor will sense an existing level of illumination, a time related function, or the absence or presence of individuals in the space (and, therefore, the need for any illumination). Historically, photocells were used to sense the darkness of the sky and that it was time for outdoor street and parking lot lights to be turned ON or OFF. These same devices can be used to sense the brightness of the sky in order to determine if indoor electric lighting is required, or they can sense the level of interior illumination in order to determine if more or less illumination is required.

Time of day is a useable criterion to turn lights ON in the morning when people come to work and shut the lights OFF at the end of the working day. A fixed time interval control is frequently used for sun lamps or heat lamps where the extended operation of the lamp may be hazardous to health or damaging to a process.

Very low use areas in buildings may not require illumination except when the space is occupied. Typical applications include warehouse aisles, library stacks, storage rooms, filing rooms, lobbies, restrooms, and small offices. Sensing the presence of an individual implies that illumination is necessary and, conversely, if no one is present, then artificial illumination is not necessary.

The human element should not be forgotten as a Sensor. Man can sense illumination levels, presence of himself and/or others in a space, and the time of day at which a particular function is to be performed. In some applications, man is a better Sensor, but generally, the devices described below are preferred because of reliability, repeatability, dependability, accuracy, and the inability of man to be at all places at all times.

2.2.2 Photoelectric Devices

A Photoelectric Device is an integrated package consisting of a photocell that produces a change in electrical characteristics with changes in incident light and an electrical amplifier that takes the small electrical signal produced from the cell and amplifies it to a power level where it can operate other equipment. The integrated package usually includes a power supply to provide the proper dc voltage for both the photocell and the amplifier.

There are two principal ways in which a photoelectric device may be used--ON-OFF, and proportional dimming. In an ON-OFF device, a relay is usually packaged as an integral part of the device. The relay operates when the light intensity which reaches the cell equals a predetermined level. The light level at which the relay operates is adjustable on some devices and fixed on others. The relay is usually an electro-mechanical device which operates the opening and closing of one set of "dry" contacts (see 2.4.3, Control Devices, for an explanation). This device, consisting of photocell power supply, amplifier and relay, will usually close its relay contacts at a given lighting level and open the relay contacts at a lower lighting level. This characteristic, known as hysteresis, prevents the relay from chattering (turning ON and OFF repeatedly) if the lighting level is exactly at the switching point.

When a relay is included as part of the photoelectric device, then the complete package is a combination of Sensor, Decision Element, and possibly Control Device. The light level at which the relay operates is the decision function and may be preset or adjustable. The relay contacts are a Control Device which may operate a Controlled Device directly or may in turn operate a larger Control Device for the control of large amounts of power.

For proportional dimming, the built in amplifier is designed to produce a voltage that is proportional to the light intensity reaching the cell. The amplifier may have a built in relay to shut off the output voltage when the light level is below a given minimum level. This device, consisting of photocell, power supply and amplifier, should be repeatable giving the same output voltage for a given light level regardless of whether the given level was reached from a higher initial level or from a lower initial level.

The photocell, or sensor, is a semiconductor device that has two characteristics: electrical and spectral. Electrically, the cell may be a diode, a transistor or a conductive element whose parameters change as a function of the spectral energy input to the sensitive surface. The particular amplifier performance and circuitry will depend upon the specific electrical characteristic. No attempt is made in this Handbook to design the electrical amplifier circuitry since the cell and the amplifier are typically an integrated unit.

The spectral response defines how the cell reacts to light. Generally, it is desired that the cell have photoptic correction so that the cell performance will correspond to the performance or sensitivity of the human eye to different wavelengths of lights. Directionality for control is obtained by correction of the cell so that it will be more sensitive to light that is normal to the cell than it is to

light that strikes the cell at an oblique angle. If the degree of sensitivity is proportional to the cosine of the angle that the incident light makes with the normal (or perpendicular) to the cell face, the cell is referred to as cosine corrected. Most cells used in lighting control are both photopic and cosine corrected.

2.2.3 Timers and Time Clocks

Timers and time clocks consist of two functional parts--a clock which is the Sensor, and a switch which is a Control Device. The difference between a timer and a time clock is the reference starting time. A timer begins its timing when it is started, whereas a time clock is referenced to the actual time of day. In both cases, a clock is used which may be electronically, electrically or mechanically (spring) driven.

Historically, a timer is a mechanically wound device that is started by turning a pointer to the desired time interval and then releasing. Turning of the pointer winds a spring and provides the power to operate the clock, in addition to closing (or opening) a set of switch contacts. At the end of the preset time interval, the switch contacts open (or close) and timing stops.

Timers are not limited to the above description. The clock may be mechanically driven (as above), electrically operated (as a synchronous motor), or an electronic solid-state operation. Electrically operated and electronic clocks may be electrically started and, therefore, have the potential for being started remotely either by manual control or automatically from another Sensor. With either the mechanically driven or electrically operated timer clock, a dial face moves and the time interval is mechanically set. Loss of electrical power will not alter the setpoint interval, but will, of course, interrupt the actual time interval of the electrically operated timer. In most cases, electrically started timers are designed to reset upon loss of voltage as if the time interval had been completed and a full time interval would occur following a subsequent start of the timer.

Electronic solid-state timers have no moving parts (dial face) and operate on the principle of counting pulses that are generated either from the power line frequency or from a crystal with a fixed oscillating frequency. Functionally, the time interval is obtained by electrically (with switches) setting a solid-state counter to the number of pulses to be counted. When the total count is reached, a solid-state relay is operated, providing an output signal to other equipment.

A time clock, being referenced to time of day, utilizes either the synchronous motor or the electronic solid-state counter principle. The synchronous motor type is the more familiar and typically consists of an electrically operated synchronous motor that drives a clock face. The clock face moves and is designed so that specific times during the day can be selected by the appropriate placement of tabs on the clock face to operate a set of switch contacts ON or OFF. The clock face may be designed for 24-hour operation whereby a given setting (to turn ON or OFF) is repeated every 24 hours. A seven-day clock face permits separate and different ON and OFF settings for each day of the week. Thus, a weekend schedule can be made that will be different than the other days of the week. A further refinement of the seven-day clock is the astronomical time clock which, when set for the proper earth latitude and time of year, will automatically correct time settings as the time of sunset and sunrise change throughout the year.

It should be noted that there is a minimum time interval between adjacent ON and OFF selected times due to the physical size of the tabs that are used to select time of day and to operate the switch. That time interval could typically be between ten minutes and one hour, with the former associated with 24-hour clocks and the latter with seven-day clocks.

There are various specialty items such as those that are designed for cycling (automatically repetitive timer) or for multiple programming (two or more switches independently controlled by the same clock). Manufacturers' catalogs should be consulted for other special purpose functions.

For time clocks that are electrically operated, it is usually desirable to maintain clock operation even if there are momentary or short-term power outages. An option that is available on many time clocks is a mechanical carry over that can keep the clock operating for 4 to 24 hours without any electrical input. This option keeps the clock running so that resetting of time of day is not required after every power outage, and is especially desirable in areas where outages are frequent.

A time clock, using the principles of microprocessors and crystal controlled digital clocks, is a very powerful control element. Multiple programs (separately switched circuits) with multiple ON-OFF functions for each circuit can be programmed independently for each day of the week and for specific holidays within the calendar year.

The minimum time interval in the electronic time clock is less restrictive than with synchronous clock motors where minimum intervals of one minute or less are available, regardless of whether the clock is 24 hour or seven day. The

astronomical time feature is generally not available in electronic time clocks. However, if the time clock is part of a programmable microprocessor, the astronomic feature could be programmed.

Loss of electrical power to an electronic solid-state time clock could result in loss of not only the time of day reference, but also of the entire program. To prevent this loss a battery can be provided to continue operation for hours or days (depending upon the battery capacity) in the event of an electrical power failure.

In terms of control system components, the clock mechanism, whether synchronous motor or electronic solid state, is the Sensor. Setting the time interval on a timer or time of day to trip using mechanical tabs or electrical input signals on a time clock is the Decision Element. The actuated switch or electronic relay is a Control Device, and directly or indirectly through another Control Device (such as a relay) operate the Controlled Element.

2.2.4   Presence Detectors

Any of the devices typically used in intrusion detection systems can be applied to lighting control. In lighting control applications, it is not necessary to have as high a sensitivity because generally there is no conscious effort to evade the sensor. Limiting of sensitivity reduces the probability that a detector will operate the lights when not required to do so. Several different principles of operation are described below.

A Pressure Mat is a foot operated switch that may be placed under a carpet or mat at the entrance of a given space. The pressure mat consists of thin tapelike strips of wire enclosed in clear vinyl. Foot pressure at any place on the mat causes adjacent strips of wire to touch each other and thereby close the switch. There are only two wires from the mat and they are connected as any control switch would be connected. There is no continuous standby power required, and the current rating is typically for control level (usually one ampere). The vinyl enclosure makes the mat waterproof permitting floor washing to be accomplished without de-energization of the circuit.

Microwave (radar) Detectors establish a steady-state field of reflected energy. The OFF setpoints on these devices are established in a room empty of people but full of furniture. The added presence of people or other large objects will disturb the field and, through internal electronic amplification and signal conditioning, will operate a relay. This relay like any switch can be used to activate lighting systems. Microwave systems are most

successful in covering large and relatively unconfined areas such as open office plans and open drafting areas, and are least successful in small rooms (since microwaves penetrate walls).

Ultrasonic Detectors operate like microwave detectors, except that the steady-state field is of sound energy of higher frequencies than the ear is sensitive to. These detectors lack the sensitivity of the microwave detector and are subject to ambient noise problems. Ultrasonic systems are best at detecting movement in confined areas such as small offices, and least successfully applied to static groups of people or larger spaces. False operation can occur due to the movement of curtains or drapes when a ventilation system is turned ON or OFF unless appropriate sensitivity adjustments are made.

Passive infrared Detectors sense a steady-state field of natural infrared energy and await a disturbance or change from the established steady-state value. Unlike the micro-wave and ultrasonic detectors, they do not emit a field to be disturbed. These devices are particularly effective in private offices and spaces up to 200 square feet at detecting static human presence, since there is a detectable level of infrared energy involved in human breathing and other general body functions. Sensitivity to other non-human activities could limit its usefulness. For example, the operation of a ventilating system or a changing sun position could change the temperature and, therefore, the amount of infrared energy radiated from objects in the space. At least one system is available that contains a band pass filter which rejects slow changes due to sun or ventilating system oper-ation and only responds to human body movements. Because the infrared energy behaves much like light, "lenses" can be used to widen or narrow the detection zone.

2.3   DECISION ELEMENTS

2.3.1   General

The function of the Decision Element is to determine the
need for increased or decreased illumination. The Sensor
defines an existing illumination level, a time related
function, or the presence of individual(s) in the space. The
Decision Element then compares this information with a
desired condition and makes a decision on whether or not to
change the illumination level. If the decision is to change
illumination, then a signal to operate the Control Device is
given.

Where the Sensor is Man, the decision is usually made by
Man also. Where the Sensor is one of the devices described
in Section 2.2, the decision function may be accomplished by
a comparison of electrical signals or by a comparison of
computer logic words. In non-computer systems, the Decision
Element is a part of the Sensor package.

It is often necessary to make a different decision on
operation of a lighting system with the same Sensor input. For
example, a boardroom or ballroom might be used for different
activities necessitating different lighting conditions. In
addition, it may be necessary to transfer control of the
lighting system from a central location to local control for
audio-visual presentations. The use of control equipment
that may include microprocessors may be desirable.

2.3.2   Integrated Packages

The Decision Element used in an ON-OFF photoelectric
device is an electronic comparison between an electrical
signal which is proportional to the measured illuminance at
the photocell and a reference electrical signal set by a knob
or screwdriver adjustment to a potentiometer. When the
measured input signal is greater than the reference signal,
no additional illumination is desired, and when the input
signal is less than the reference signal, illumination is
desired. When the Decision Element determines the need for
ON or OFF condition of the lighting system, an electrical
signal is generated to operate a relay. Similarly, with the
electronic presence detectors, the Decision Element is an
internal electronic comparison between an input electrical
signal proportional to the measured field strength received
and a preset reference electrical signal that is proportion-
al to the field strength that identifies that there is someone
in the space.

For an analog photoelectric sensor, the photocell out-
put is an electrical signal proportional to the actual

-17-

illuminance incident to the photocell. This signal is compared with an electrical reference signal that is proportional to the desired illuminance. The Decision Element then provides an output electrical signal that is proportional to the difference between the actual and desired illuminances. Of course, the output signal is limited in magnitude to electrical values that will operate the lighting system at maximum and at minimum output.

2.3.3 Programmable Controllers

A Programmable Controller is an electro-mechanical or electronic solid-state microprocessor based device that has the ability to make decisions based upon multiple inputs from Sensors and/or desired output conditions. It is general and versatile, and depends upon the versatility of the programmer to determine how useful it can be. A clock is usually included in solid-state controllers so that decisions can be referenced to time-of-day and day-of-week or year. In order to prevent loss of programming information in solid-state controllers in the event of a power failure, many systems have a small battery sized only to maintain memory until power is restored. Electro-mechanical controllers do not need a battery to preserve the memory because the program is typically hardwired or patched with jumper cables or diode pins between the electro-mechanical components.

An Architectural Controller is a programmable controller that is designed for a specific purpose to accept Sensor inputs and permit multiple decisions to be made, such as:

- Multi-scene preset for a functionally fixed space, such as a conference room where each scene corresponds to a particular function of the space, e.g., business meeting, speaker presentation, screen presentation, casual.

- Control re-assignment of control zones for a functionally flexible space, such as a space with moveable partitions, e.g., conference rooms, divisible cafeteria, divisible exhibition space, etc., where a local control station is provided in each of the smallest possible spaces and it is desired that control of a larger subdivision (combination of several small spaces) be assigned to only one of the local control stations.

- Multi-station "take control" for a multi-use space, such as a meeting room or auditorium, where it is desirable to have the control station in command change during an activity, e.g., from control room to lecturn.

Architectural Controllers often include the function of a Control Device particularly when dimming is included.

2.3.4   Energy Management Computers

Energy Management Computers are used to remotely control and monitor the building environmental conditions as well as equipment operation. Many are capable of making the decisions necessary to coordinate the lighting and HVAC systems, monitor energy consumption, and vary control schedules.

Computers are available in a variety of forms. Most provide some means of entering information either through a tape, card reader, or keyboard. This allows for quick control changes due to variations in seasons, holidays, layouts, functions, or energy. Several computers have hard copy printouts, telephone interfacing, power outage provisions, and visual displays and/or CRT screens to reveal past, present and future control decision. They can be programmed to monitor power demand, control load shedding, and meter individual loads.

Large buildings or complexes warrant a computer to provide efficient control and monitoring from one central location. Monitoring each connected load enables the user to maximize the potential for efficient utilization of energy within the building. Hard copy printouts provide a permanent record of the energy usage over a specific time span. This system provides 24-hour monitoring without the constant need for human assistance.

The greatest advantage of Energy Management Computers is their ability to be programmed to perform on time or input functions and to render selected results. In programming, the owner is able to perform virtually any function of any other type of controller. For energy management, these computers, with the appropriate Sensors, generally can provide the following types of control:

- Presence

- Calendar time

- Timer

- Daylight

- Demand limiting (by load shedding or dimming)

- Proximity/process need

In addition, the Energy Management Computer is usually programmed to make decisions involving the use of energy for the entire building simultaneously so as to maximize overall efficiency and minimize energy costs. Computer systems, being electronic, may be connected, or "interfaced", to virtually every other building system inexpensively. In addition to controlling the electric lights, the computer could be monitoring temperatures, velocities, efficiencies, and other aspects of the mechanical system and controlling them for peak effectiveness at all times.

2.4 CONTROL DEVICES

2.4.1 General

Changes in illumination can generally be made by changing the voltage that is applied to the "Controlled Element". This change in voltage may be binary, that is either ON or OFF, or it may be analog ranging from zero to some maximum value. ON-OFF control is provided by switches, circuit breakers, relays and contactors which make a physical break in the circuit conductors supplying the lighting system with electrical power. Analog voltages are obtained either from potentiometers which are manually operated, or by solid-state devices which are electronically operated.

2.4.2 Switches and Circuit Breakers

Switches and Circuit Breakers are similar in that they are mechanically operated. The typical switch in a home is manually operated and serves to turn lights ON or OFF depending upon whether a person is entering or leaving a room. A switch for a refrigerator light is usually operated by the door when it is opened or closed manually.

Switches may maintain their position or be momentary. A momentary contact switch is operated only when pressure is applied to its operating handle and it returns to its original state when pressure is removed. Some of the various forms of switches and how they may be depicted schematically are shown in Figure 2-2.

A Circuit Breaker is a switch that has a means of opening the circuit automatically if too much current flows through the circuit breaker. A circuit breaker is not typically designed to be operated on a daily basis for control of lighting. There are, however, certain circuit breakers designated "SWD" which are designed, tested, and listed by a testing laboratory for use as a switch for the daily control of lighting.

Typically, power is supplied to a lighting circuit from a branch circuit panelboard through a circuit breaker. If all of the lights are to be turned ON manually at the same time (one control zone), then the circuit breaker may be used for control. If the lights are to be turned ON individually or in small groups, power is provided continuously to the entire circuit and the circuit breaker is left ON. Individual switches may then be used to control individual lights or groups of lights as control zones.

SINGLE POLE | DOUBLE POLE

THREE-WAY | FOUR-WAY

MOMENTARY CONTACT TRANSFER
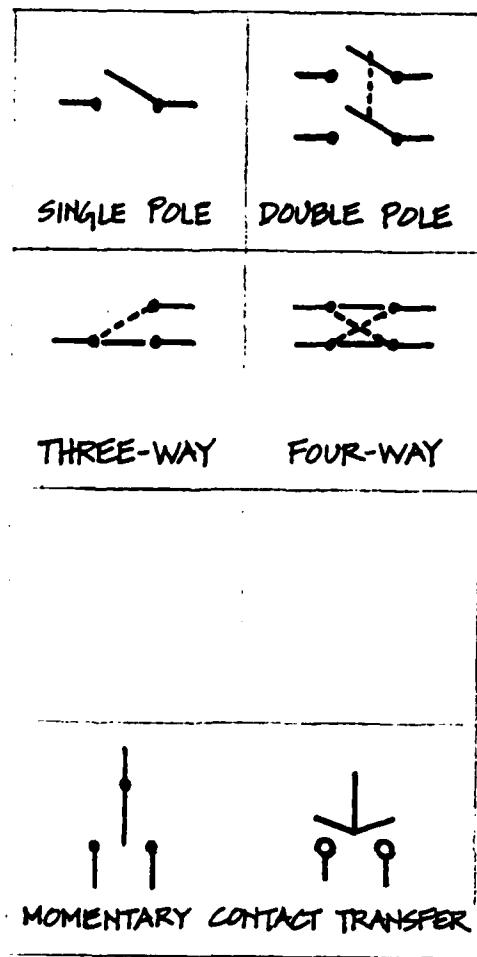
MANUALLY OPERATED SWITCHES
FIGURE 2.2

2.4.3   Relays and Contactors

A Relay is a switch contact that is operated by an electrical signal rather than by manual operation. Relays may be either electro-mechanical or solid state. An electro-mechanical relay consists of a coil or solenoid and sets of contacts. When voltage is applied to the coil, a magnetic field is set up which attracts or pulls an armature toward the coil. Movement of the armature will move one contact from each paired set of contacts either by direct attachment to the armature or through a lever or plunger. Movement of the armature, therefore, changes the electrical continuity of the contacts. Contacts that were electrically open prior to energizing the coil will close (called Normally Open, NO, or type "a") and contacts that were electrically closed prior to energizing the coil will open (called Normally Closed, NC, or type "b").

The coil or solenoid may be designed to be operated by an alternating current or a direct current. The voltage required to operate the coil may be as low as 6 volts, or as high as 277 volts. Generally, more voltage is required to operate a coil than to hold the contacts in place once it has been operated. Typically, 85 percent of rated voltage is required to operate and about 75 percent of rated voltage is required to hold the contacts.

The output contacts are electrically isolated (dry) from the solenoid so that the ratings of the contacts, in terms of current and voltage, can be and usually are different than the coil. Because of the electrical isolation of relay contacts, several different circuits can be operated from the same relay or many circuits can be simultaneously operated by energizing the coils of several relays with the same electrical signal voltage. Sets of contacts can be connected together mechanically and/or electrically to achieve transfer functions such as break-before-make and make-before-break.

The difference between relays and contactors is in use rather than function. Relays are used for control and logic circuits so that their contacts have a low current rating; typically, 5, 10, or 20 amperes. A contactor is used to control power such as motors or lighting circuits and the minimum contact rating is typically 15 or 20 amperes.

Relays (and contactors) are maintained in the operated position by the continual application of voltage to the coil or solenoid unless a mechanical means is provided to hold the armature in place. If no mechanical means of holding is provided, the relay (or contactor) is termed "electrically held" and where a mechanical hold means is provided, the relay (or contactor) is termed "mechanically held", "mechanically latched", or simply a "latching type". Mechanically held

contactors are used where the hum noise from electrically held contactors is not desired.

A latching type relay (or contactor) requires only a momentary pulse of voltage to the operating coil. The length of the pulse (time duration) must be long enough for the armature to move into its operated position and for the latch to hold. Release of the mechanical latch is usually accomplished by applying a momentary pulse of voltage to a separate unlatching coil. Latching type relays are not designed for the continual application of voltage either to the main (or latching) coil or to the unlatching coil. Continuous application of voltage typically results in audible hum and may result in burnout of the coil.

There are two ways of providing the momentary operating voltage: external circuit and internal coil clearing circuit. Low voltage operated latching relays for lighting controls are typically operated from momentary contact switches such that relay operating voltage is applied only while the control switch is manually operated. Where automatic means are provided to operate the relays, an external circuit must be used to provide only a momentary operating pulse of a limited time interval. For lighting contactors where the coil control voltage is continuously provided through a time clock or a photoelectric device, coil clearing contacts are provided on the contactor. The coil clearing contacts are mechanically opened by the contactor after the latching mechanism has operated to hold the armature. The coil clearing contacts open the circuit to the operating coil even though the control voltage is continuously applied. Similar use of a contactor contact in the unlatching circuit prevent continuous voltage from being applied to the unlatching coil. Schematic diagrams of an electrically held and a mechanically held or latching type contactor are shown in Figure 2-3.

Solid-state relays consist of a thyristor which is generally a silicon controlled rectifier (SCR) for the contacts and a gate signal to the SCR instead of the coil. The SCR is a unidirectional device which passes current in one direction only. They are normally used in pairs. TRIAC systems which pass current in either direction are generally limited to use with low current loads, and operate similarly to a pair of SCR's connected in inverse parallel circuit. The logic operation is similar to the electro-mechanical relay with the added advantage that there are no moving parts to fail. Internal circuitry can be specified so that the relay will operate with a continuous control signal or with a momentary control signal depending upon which signal is available. The speed of response is much faster for the solid-state relay but that is usually of no consequence in a lighting control application. One disadvantage of the solid-state relay is that there is not complete electrical iso-
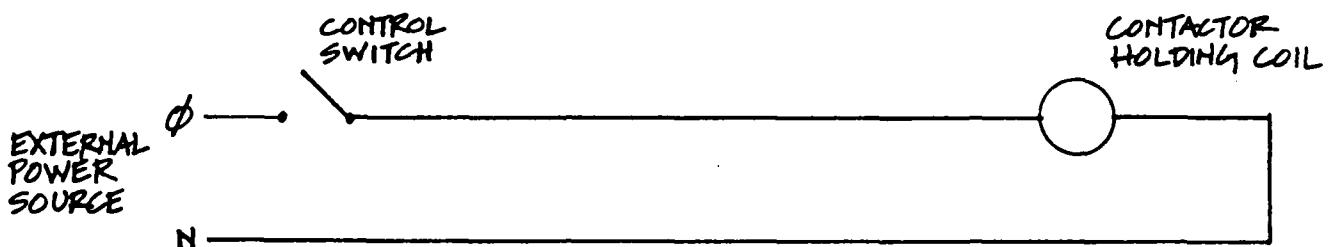
A. ELECTRICALLY HELD
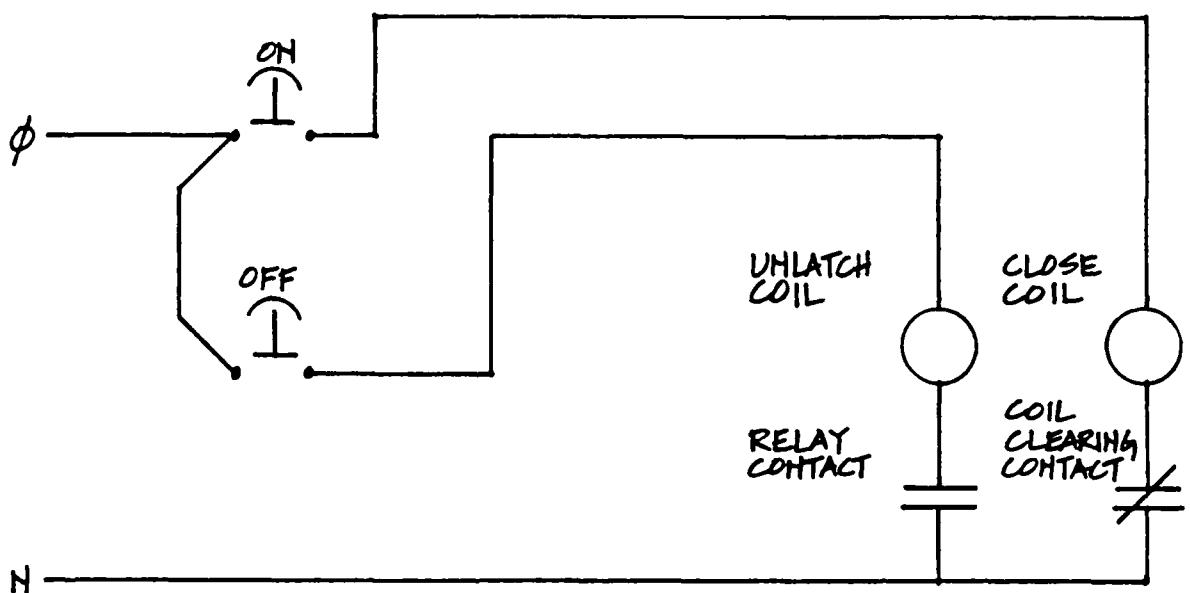
B. MECHANICALLY HELD

CONTACTOR CONTROL CIRCUITS
FIGURE 2.3

lation between input signal and output power. If the Controlled Element operates at 277 volts, then the Control Device must also operate at the same voltage. Input to the Control Device from the Sensor/Decision Element is usually made at lower voltages through the use of coupling transformers.

Time delay relays are similar to electrically held electro-mechanical relays with the addition of a means of delaying the change of contact position after energizing and/or de-energizing the operating coil. A delay after energizing the coil is termed "pick-up" delay and a delay after removing voltage from the coil is termed "drop-out" delay. The delay function can be accomplished by either pneumatic or by electronic means. A pneumatic time delay uses a bellows and orifice to prevent the contacts from moving immediately. An electronic time delay (as part of an electro-mechanical relay) operates on the principle of the charge or discharge time of a resistance-capacitance circuit. Both types can be adjustable. The electronic type is generally more accurate and covers a wider timing range. Electronic time delay as part of a solid-state relay is still more accurate and can cover a very large or small time interval by counting the pulses of an electronic clock (see Section 2.2.3).

2.4.4 Potentiometers

A Potentiometer is a device with a variable resistance that provides a voltage which varies with the position of the operating handle. The voltage may be the reference signal in a Decision Element as described in Section 2.3.2, or it may be the reference signal in a dimmer as described in Section 2.4.5. A schematic of a potentiometer is shown in Figure 2-4. A constant voltage is applied to terminals 1 - 2. The output is taken between terminals 2 - 3. As the wiper or moveable contact is varied from one end of the resistor to the other, the output voltage varies from zero, when the wiper is near terminal 2, to a maximum when the wiper is near terminal 1.

The output voltage may be directly proportional to the wiper's physical position or it may be non-linear. The amount of non-linearity depends upon the relative value of potentiometer and load resistance, or on the manner of winding the potentiometer.

For lighting system control, a potentiometer is typically part of an integrated assembly and is not purchased or wired separately.

1

—MOVABLE CONTACT POINT

3

2   2
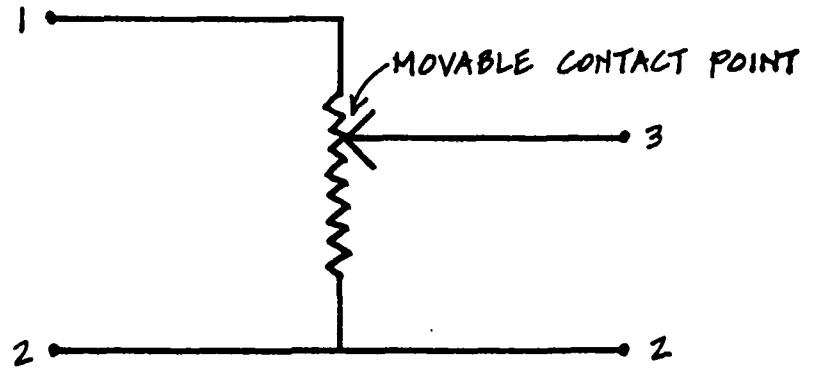
POTENTIOMETER
FIGURE 24

2.4.5   Dimmers

A Dimmer is a device generally designed to provide reduced voltage to a lighting system. Voltage is reduced by inserting a series resistance in the circuit, by transformer action, or by electronically switching out a portion of the alternating voltage cycle. Incandescent lighting is easily dimmed by reducing voltage. Fluorescent and high intensity discharge lamps can be dimmed by reducing voltage or by the use of special ballasts for dimming.

Series resistance is rarely used because energy is dissipated in the resistance. This device is not only inefficient, but is also bulky and thermally unacceptable. Series resistance was extensively used before the advent of solid-state devices for dimming of stage lighting, where the size of the equipment and the heat dissipated from the resistors was incidental to the continuous dimming control that could be obtained. For fluorescent and high intensity discharge lighting using a dimming ballast, a variable resistance is often used to electronically control the ballast output. The variable resistance is usually a potentiometer as previously described. Since the resistance is in the control circuit and does not carry full load current, the loss is small. The resistor can be made small enough to fit in the space of a wall switch.

Voltage can be reduced by using an autotransformer with a sliding contact. The sliding contact makes an electrical contact with successive turns of the autotransformer resulting in an output voltage at the sliding contact that varies from zero to the maximum applied voltage. The variable voltage autotransformers, sometimes known by the trade name "VARIAC", are large, bulky, and quite heavy. They can be manually operated or motor driven and were often used for large auditoriums or theaters. Several autotransformers can be ganged on a common shaft and be driven by one motor. Large groupings of autotransformers require special consideration due to their size and weight. There is no radio frequency interference (RFI) generated by this device and its heat loss, which must be dissipated, may be 5 to 10 percent of the transformer rating. A switch can be added to the operating shaft to provide a positive shutoff at near zero output voltage.

Electronic dimmers operate on the variable phase angle conduction principle. Thyristors are solid-state switching devices, turned on (gated) at different times (phase angles) of the alternating current cycle. Figure 2-5a shows a sine wave that represents a full electrical cycle. If the turn on (gating) of the thyristor is delayed approximately one-eighth of a cycle on both the positive and the negative half cycles, the output wave shape will be as shown in Figure 2-5b. Since a portion of the wave is missing, both the average
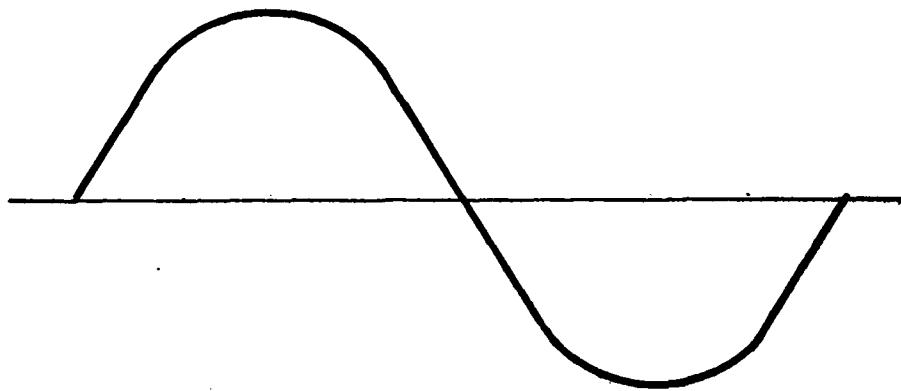
A. FULL SINE WAVE
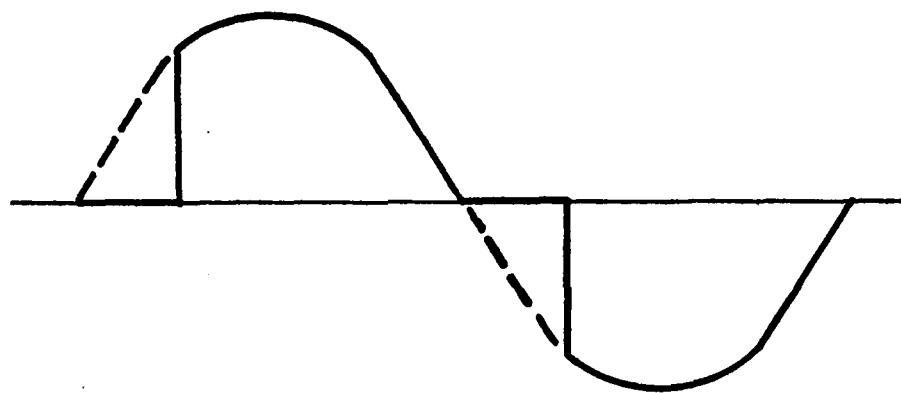
B. GATED SINE WAVE
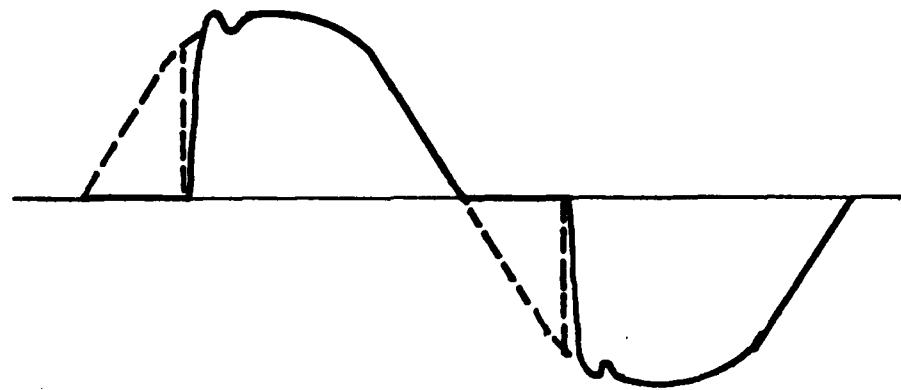
C. GATED SINE WAVE WITH CHOKE

VARIABLE PHASE ANGLE CONDUCTION
FIGURE 2.5

as well as the root-mean-square (RMS) voltage and current are reduced, achieving the intended objective.

The basic circuit for a thyristor dimmer is shown in Figures 2-6 and 2-7. The thyristor may be an inverted pair of SCR's, as shown in Figure 2-6, or a single TRIAC as shown in Figure 2-7. TRIAC's are typically used for low power applications such as wall box dimmers, while SCR's are used for handling current in the range of 10 amperes and above. In addition to the thyristor device(s), there are several resistors for biasing the gate so that it will not fire as well as a potentiometer to set the firing level. The thyristor control potentiometer and miscellaneous components are encased in a package usually designed to replace the conventional wall switch. The control potentiometer can be either rotary or linear (slider) and will usually have a switch at one end of travel for positive shutoff.

For small power applications (up to 1,000 or 1,500 watts at 120 volts) the thyristor does not need any forced air cooling. Cooling is usually provided by heat sink fins on the dimmer cover that provide additional surface area for convective air cooling. Special care must be taken in ganging dimmers in order to prevent overheating of the solid-state components. For applications of 2,000 watts or higher, the thyristor normally requires forced air cooling. The dimmers are typically mounted in an equipment room in racks where proper ventilation can be provided. The control potentiometers are generally mounted remotely where they can be conveniently operated and wired to the remote dimmer rack. No forced ventilation is required for the potentiometers. Generally, the control signal is provided by varying d.c. voltage from 0 to 24 volts.

Electronic dimmers generate radio-frequency interference (RFI) because of the high speed switching of SCR's and TRIAC's. The very fast rise time of the current and the high switching speeds (see Figure 2-5b) result in the generation of harmonically related radio-frequency signals. Two basic types of RFI may be generated by thyristor switches. One is radiated RFI which is radiated directly into the air as a radio signal from the device, lighting system, or unshielded wiring. This type is of a low intensity and is of consequence to "sensitive" electronics and electronic wiring in the direct proximity of the source. Simple shielding of the source of RFI, such as the enclosure of wiring in conduit, or maintaining minimum proximities, will generally eliminate interference. The second type is conducted RFI which is carried through the power lines and will seriously affect audio systems, computers, correcting clocks, and other "sensitive" electronic devices that are connected into the same electrical system. This type of RFI can be minimized by connecting a simple choke (L-C filter) in series in the power

GATE 1

LOAD

K1 G1
SCR₁

G2 K2
SCR₂
GATE 2

"REACTOR"
or
"CHOKE"

(OPTIONAL)
SWITCH & OVERCURRENT
PROTECTION

POWER
SOURCE
(MUST BE A.C.)

THYRISTOR DIMMER
WITH SCR'S
FIGURE 2.6

— TIME →

INPUT VOLTAGE (NOMINALLY, 120V RMS)

VOLTAGE APPLIED TO GATE
ACROSS K-G POINTS (ABOUT 5V)
K1-G1
K2-G2

CURRENT THROUGH SCR-1
CURRENT THROUGH SCR-2

= ACTUAL POWER
DELIVERED TO
LOAD.

TURNED "OFF"
(ABOUT 35% SHOWN)

TURNED "ON"
(ABOUT 65% SHOWN)

RESULTANT
INPUT TO LOAD.

LOA

TRIAC

G K
GATE

"REACTOR"
OR
"CHOKE"

(OPTIONAL)
SWITCH & OVERCURRENT
PROTECTION

POWER
SOURCE
(MUST BE A.C.)

INPUT VOLTAGE (NOMINAL W., 120V RMS)

VOLTAGE APPLIED TO GATE
ACROSS K-G POINT (ABOUT 10V P-P)

CURRENT THROUGH TRIAC

THYRISTOR DIMMER WITH TRIAC
FIGURE 2.7
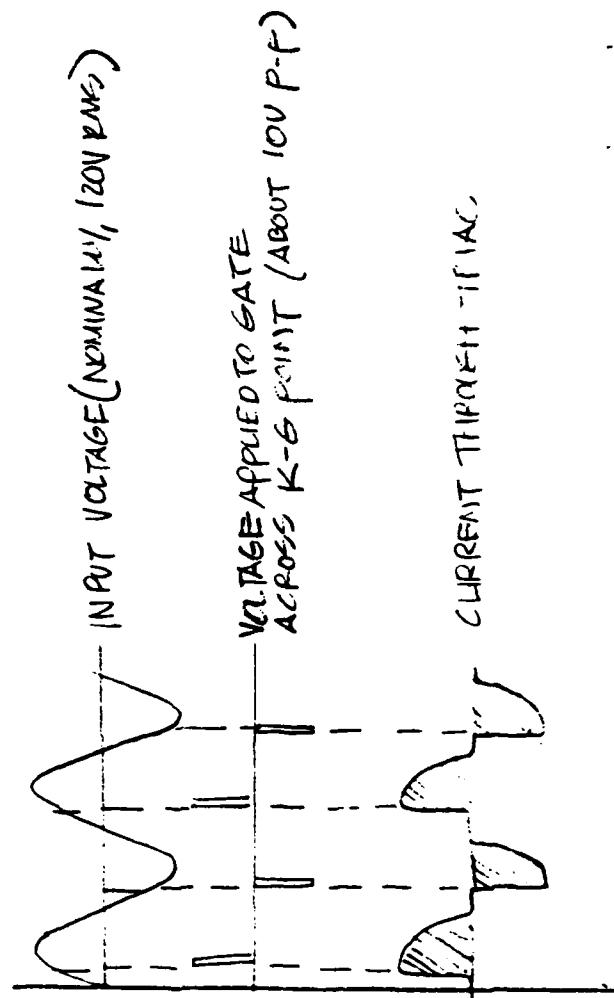
line between the thyristor device and the load. The choke reduces the conducted high frequency harmonics of the basic switching signal to an insignificant level. The inductance of the choke acts to limit the rate at which the current can increase as shown in Figure 2-5c.

Incandescent lamps tend to "sing" when dimmed. This is the result of the unfiltered high frequency harmonics which will vibrate the lamp filament at a resonent audible frequency. This condition is virtually eliminated with the addition of a choke as used for RFI filtering.

A fluorescent dimming system electronic ballast is not the electronic dimmer described above. The electronic ballast (described in Section 2.5.3) usually requires a small d.c. control voltage which is obtained manually from a remote potentiometer or automatically from an electronic control system.

2.5   CONTROLLED ELEMENTS

2.5.1   General

The ultimate purpose of a lighting control system is to turn ON or OFF or dim an incandescent lamp, a fluorescent lamp, or a high intensity discharge (HID) lamp. Except for the incandescent lamp, all of the others require a ballast for successful operation. As a Controlled Element, the incandescent lamp can be treated separately. For the fluorescent and HID lamps, the ballast and lamp should be treated together as a unit.

2.5.2   Incandescent Lamps

Incandescent lamps produce light by passing current through a filament that gets sufficiently hot to "luminesce" (or emit light). The color temperature is a function of the current through the filament and, therefore, of the applied voltage. The efficacy of light produced (lumens per watt) is a function of the color temperature of the filament increasing as the color temperature increases. It has been shown (see IES Handbook) that the relationship between applied voltage and efficacy is:

$$\frac{(\text{lumens per watt})_1}{(\text{lumens per watt})_2} = (\frac{\text{volts}_1}{\text{volts}_2})^{1.9}$$

In addition, the color temperature of the emitted light in degress Kelvin is a function of the applied voltage:

$$\frac{(\text{color temperature})_1}{(\text{color temperature})_2} = (\frac{\text{volts}_1}{\text{volts}_2})^{0.42}$$

Thus, as the applied voltage to an incandescent lamp is reduced in order to conserve energy, the efficacy (lumens per watt) decreases and the color shifts towards the red end of the color spectrum and away from the blue end.

To evaluate the reduction in power consumption that results when an incandescent lamp is dimmed to a lower lumen output level, the following relationship applies:

$$\frac{\text{lumens}_1}{\text{lumens}_2} = (\frac{\text{watts}_1}{\text{watts}_2})^{2.125}$$

A 30 percent reduction in lumen output is produced by a 13 percent reduction in input power. An additional benefit obtained by incandescent dimming is increased lamp life. The increase is very rapid as shown in the following relationship:

$$\frac{(\text{lamp life})_2}{(\text{lamp life})_1} = (\frac{\text{volts}_1}{\text{volts}_2})^{13}$$

2.5.3 Ballasts

Ballasts for fluorescent and HID (high intensity discharge such as mercury vapor, metal halide, multivapor, high pressure sodium) lamps serve three purposes:

- They provide the proper lamp arc voltage through transformer or autotransformer action.

- They provide the proper voltages as necessary for filament and/or igniter heating.

- They provide a positive resistance characteristic to counter the negative resistance characteristic of arc discharges. Without this characteristic, arc current would rapidly increase uncontrolled until rapid burnout occurred.

From a control point of view, there are only two types of ballasts--standard and dimming. The standard ballast provides a fixed excitation to its associated lamp when energized at a fixed voltage. Reduction of the excitation voltage will reduce the voltage to the lamp. A dimming ballast is designed to operate at rated voltage and will provide multilevel illumination upon application of a separate control voltage to the ballast. Dimming ballasts as of June 1983 were only commercially available for fluorescent dimming.

Standard ballasts may be core and coil, energy efficient, lag, constant wattage, autotransformer, or electronic. When operated in an ON-OFF mode, the type of ballast is immaterial with respect to the control circuitry. The type of ballast and the type of lamp may, of course, be important in the basic design of the Lighting System to provide a most efficient design. Control circuits for ON-OFF control of standard ballasts are identical regardless of the

ballast type in that voltage is either supplied to the ballast at rated voltage or the voltage is disconnected from the ballast. Rated voltage to the lamp and to the filament or igniter will result when rated voltage is applied to the ballast.

Fluorescent and high intensity discharge (HID) lamps energized from standard ballasts, except constant wattage, constant current and elecytronic types, can be dimmed by reducing the excitation voltage to the ballast. This may be accomplished with the use of previously discussed autotransformer and solid-state dimmers. In addition to the lamp voltage being reduced with reduced ballast voltage, the filament or igniter voltage is also reduced. Generally, the above lamps will not fire with reduced filament or igniter voltage, but once an arc is established, the ballast voltage can be reduced. It is, therefore, always necessary to start a lamp at full output and then reduce it. Dimming with reduced input power to standard ballasts is generally possible to 40 or 50 percent of rated light output. Below that level, the lamps often tend to be unstable and often will self-extinguish.

An important consideration in designing a dimming control system is the change in efficacy with reduced input power. It would be desirable if the efficacy did not reduce as the lamps are dimmed. The lumen output versus input power for fluorescent and HID systems are shown in Figure 2-8. It should be noted that the fluorescent system has a slightly higher efficacy (10 percent) at 50 percent input power while the HID systems have a lower efficacy (-20 percent for mercury vapor, -40 percent for metal halide, and -36 percent for high pressure sodium). These values should be compared to the incandescent system with a 54 percent reduction in efficacy at 50 percent input power.

Dimming ballasts are designed to operate at rated input voltage and provide multilevel illumination upon application of a given control voltage to the ballast. The multilevels may be discrete levels or continuous from maximum to some minimum controllable (stable) level. From a control point of view, it is immaterial whether the dimming ballast is conventional or electronic. It is only important that the lumen output can be reduced by applying an appropriate control voltage and the required power will also decrease. Dimming ballasts have an advantage over standard ballasts in that the lumen output can generally be reduced to 10 percent of rated output and, in some cases, even lower. It should be noted that, in general, the initial lamp arc from an extinguished condition must be established at rated output. Thus, except for incandescent lamps and certain electronic dimming ballasts, none of the lighting systems can have their lumen output increased gradually from an OFF condition.
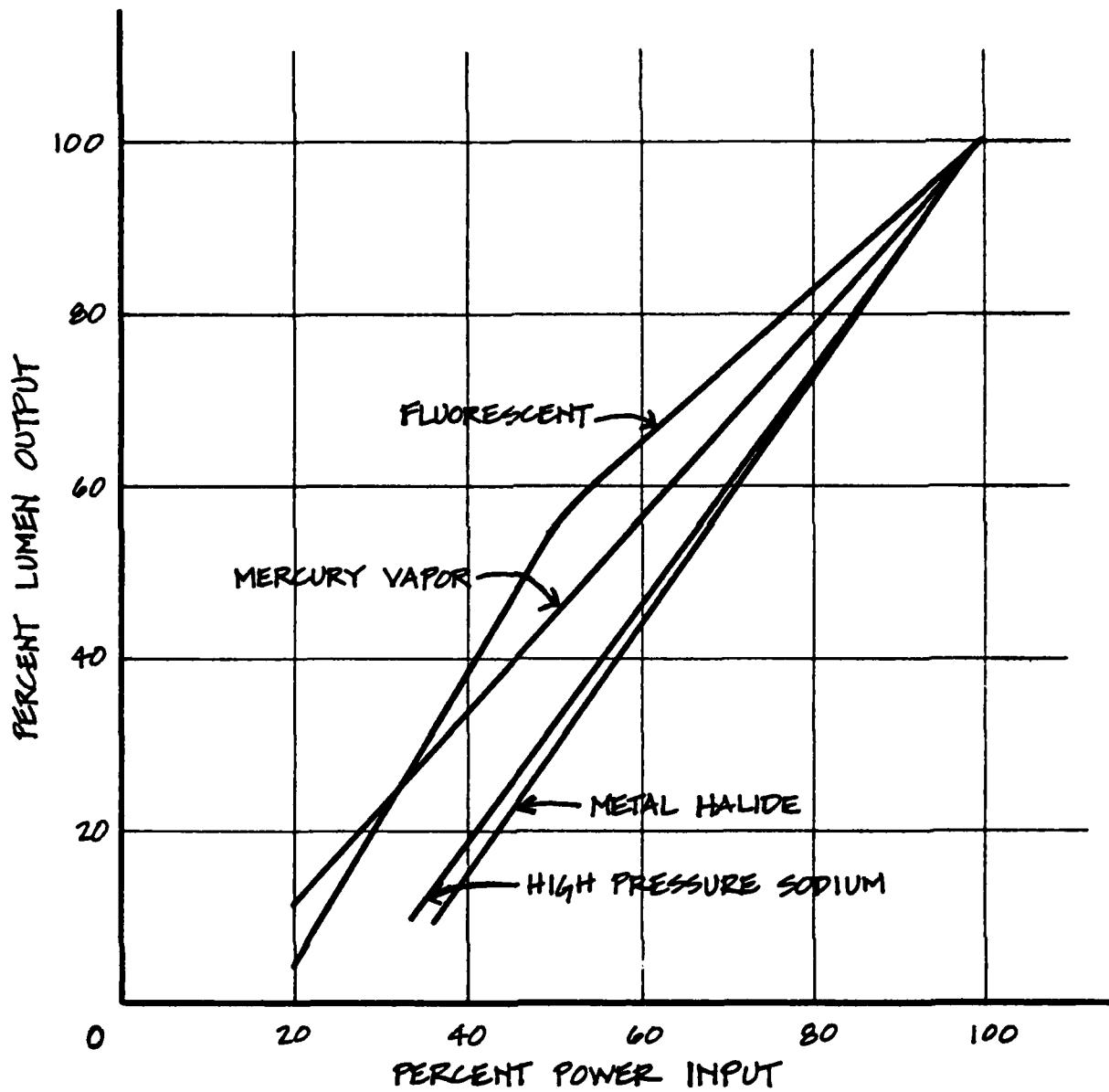
EFFICACY OF FLUORESCENT AND HID SYSTEMS
FIGURE 2.8

2.6   ENERGY COST

There is no one standard by which all utilities charge for the use of electricity. Any detailed analysis of potential cost savings requires an analysis of the specific rates that apply and an estimation of probable escalation of rates. In previous years the cost of electricity increased at the same rate as inflation. Since 1967, the increase has been at a faster rate. The Department of Energy has published tables that indicate the expected rate of increase. The tables are presently out of date, however, and escalation of energy rates faster than inflation is a fact of life. For estimating purposes, a differential inflation rate of 2 percent or 3 percent over the rate of inflation would not be unreasonable; i.e., the annual increase in electricity cost will be 2 to 3 percent greater than the annual rate of inflation.

The analysis which follows is typical of rate structures used by utility companies, but not necessarily that of a particular utility company. Each utility company has its own individual rate structure. The cost of electricity to a user depends upon whether the user is on a domestic, general service, or primary rate schedule. Each one will be described with respect to demand charge and energy charge. In principle, a demand charge, if there is one, is to pay for the generating and transmission facilities, and an energy charge is to pay for the fuel whose energy is converted into electricity.

Where there is a demand charge it is usually based upon the maximum kilowatt (kW) demand although there is at least one utility that bases demand on kilovolt amperes (kVA). The significance of the difference is that facility size is based upon load current which reflects directly into kilovolt amperes. Kilowatts is more universally measured because it is an additional output from a standard kilowatt-hour meter and requires no additional instrumentation. If power factor is high, then there is little difference between the two. If, however, power factor is low, kilovolt amperes can be significantly larger than the kilowatts which is being charged for but the kilovolt amperes is what determines the necessary facility capacity. In some rate structures, power factor is measured and additional charges made for low values.

Energy usage is universally measured in kilowatt-hours (kWH). Kilowatt-hours is a measure of the total work done and truly reflects the energy in fuel necessary to do that work (plus transmission losses).

Domestic rate class typically charges for kilowatt-hour energy consumption regardless of when it occurs during the

day. Rates may be a constant per kilowatt-hour, progressive, or regressive. Progressive rates give an incentive to use more electricity by charging less per kilowatt-hour as more electricity is used. Thus, the first block of electricity usage up to say 500 kWH per month would be at one rate while any excess over the first block would be at a lower rate per kWH. A regressive rate discourages usage by charging more per kWH for the second block of electricity than for the first block.

General Service rates are for under 600 volts and Primary Service rates are for electricity delivered at higher than 600 volts with the user owning the step down transformer and paying for the transformer losses. Small General Service rates may be similar in structure to the Domestic rate where electricity is charged only for usage and not for demand.

Large General Service and Primary Service rate structures may be very similar with only the cost per unit differing due to the economies of supplying large amounts of electricity to one location. A demand charge is typically a feature of these large services. One type of demand meter is an integrating type with a 30 minute time constant. Demands register on the meter in an amount that is proportional to the demand and the length of time that the demand occurs. Instantaneous demands do not register on the meter unless they are sustained. A demand that lasts for 30 minutes would register the full value of the electrical demand. This meter is reset at the beginning of each billing period and indicates the peak value during the period. The integrating demand meter is often used for Large General Services and the energy charge is at a constant rate per kilowatt-hour.

Demand charge structures may have a "ratchet" clause that penalizes the user for having had a large demand some time in the past. Typically, a total demand charge will consist of a rate per kW for peak demand during the current month, plus a rate per kW for the peak demand during the previous 11 months (or previous cooling season). This latter demand is referred to as the "ratchet" and may have a minimum value of a percentage (say 50 percent) of the peak demand ever recorded. It can be seen that limiting of peak demands is important because payment may be made on that demand every month for a least a year and possibly forever. It is important to note that reduction of peak demand through the use of a lighting control system may not ever reduce the ratchet demand charge.

A second means of measuring demand used on Primary Service rates is to count the number of revolutions of the kilowatt-hour meter disk in a given time interval (say 15, 30 or 60 minutes) and recording the amount along with the time of day on a permanent record tape. By dividing the number of

kilowatt-hours used in a given time period by the length of that time period results in the average kW demand during the given period. The utility company, after processing the data, may charge for peak demand that occurs during a specific time period of the day (termed "on-peak" by one utility), or they may average weekly peak demands, or some other method to determine a "billing" demand. In general, most utilities will have a "ratchet" demand charge regardless of the method of determining billing demand.

To encourage high power factor loads, many utilities will charge for low power factor demand. Power factor is determined by metering the total kilowatt-hour and the total kilovar-hour usage during the billing period and determining average power factor from the following formula:

$$p.f. \quad = \quad \cos[\mathrm{Tan}^{-1}(\frac{kVAR-Hr}{kWH})]$$

The penalty is typically a factor by which the "billing" demand is increased. It may be incremental (say 1 percent additional for p.f. between 0.80 and 0.85, 2 percent for p.f. between 0.75 and 0.80, etc.), or it may be proportional to the amount that the power factor is less than a given value (say $\frac{0.95}{p.f.}$). There is, of course, an incentive to maintain the building power factor at a high value. Note that the use of solid-state thyristor dimming tends to lower the system power factor.

Electrical energy is measured with the traditional kilowatt-hour meter. The charge may be a constant rate per kWH, a two-level per kWH rate (one for "on-peak" time, and a lower one for off-peak time), or a stepped kWH rate based on demand. This stepped rate consists of several blocks of consumption each at different rates. The size of each block is dependent upon the billing demand. The first block might be from 0 to 100 kWH per kW demand and the second block from 100 kWH per kW to 500 kWH per kW, etc. Thus, for a 400 kW billing demand, the first block would be the first 40,000 kWH and the second block would be from 40,000 to 200,000 kWH, etc. The incentive to limit demand would depend upon whether the incremental block rates are progressive or regressive.

In analyzing the economic incentive to reduce demand and/or energy usage, the specific rates are very important. It is important to recognize whether lighting control will only reduce usage or will it also reduce demand. Many analyses erroneously use an average cost of electricity determined by dividing the total monthly charge by the total

kilowatt-hour usage. This can be erroneous if the demand is not reduced, or if the reduced usage occurs at a lower incremental rate, such as an off-peak or high consumption incremental block rate.

2.7   CONSERVATION MEASURES

Conservation of energy using lighting controls is based upon two principles: use and need. Lighting should be made available only when it will be used and only in the quantity and quality necessary to perform the desired tasks. For practical economic reasons it may not be desirable to achieve the maximum conservation that is possible. It simply costs too much to provide the absolute sensing necessary for maximum conservation.

To provide lighting only when it will be used requires, as a minimum, the ability to determine that someone is present. Several sensors are described in Section 2.2 that can determine the presence of a person in the field of view of the sensor. The smaller that the sensing field of view can be made and the smaller that the lighting control zone (see Section 1.4) can be made, the greater the level of energy conservation that can be achieved. If it can be determined when an individual is at his work station, and if the lighting for his work station is independent of all other work stations (a separate lighting control zone), then lighting can be provided only when he is at that station.

There are three considerations that interfere with this ideal implementation of presence controls: size, mobility, and adjacency. A work station or control zone may be a large area, with the worker moving from task to task within his work station. The worker may be very mobile, moving from work station to work station at frequent intervals. A work station may be too large or too small to be illuminated by a given complement of luminaires, thus necessitating enlarged or overlapping lighting control zones covering multiple work stations. There is, in addition, an aesthetic aspect to adjacency where in large open spaces it "doesn't look good" if some luminaires are ON and others are OFF resulting in a non-uniform luminous ceiling.

Compromises are generally required to satisfy the above conditions. The compromises will generally be in the direction of providing illumination at times when it is not needed to insure that illumination is always provided when it is needed. A level of conservation still may be achieved with this philosophy. The alternative to compromise will typically result in the users bypassing of lighting controls and ultimately in an increase in energy consumption.

To provide only the quantity of illumination necessary to provide for visibility of the task in a given lighting control zone requires the ability to measure or predict the available illumination at each task and to determine the illumination necessary for the task. Measurement may be extensive and

complex if multiple tasks are performed in close proximity to each other. Determining the amount of illumination necessary for clear and productive visibility for each individual for each task with any degree of precision is a tremendous undertaking which requires careful testing, measurement, and analysis of each task and user. This study is part of Lighting System design and is beyond the scope of this Handbook. If the measurement of available light and the needed amount of light can be determined, then dimming and/or ON-OFF systems can provide the necessary control and adjustment.

Between the ideal and practical reality is a compromise position that results in both conservation of energy and return on investment. Some generalizations that have been found in the past to be economically viable are:

- Dimming of luminaires to meet maintained footcandle requirements rather than initial footcandle levels.

- Larger spaces may require fewer photocells per square foot.

- Presence detectors for one-man offices where the space is occupied several hours a day or less.

- Two lighting systems for spaces with two tasks requiring variation of 5 to 1 or greater between illumination levels.

- Two level lighting system for normal use and for housekeeping.

- Time of day control of housekeeping functions.

- Equi-illumination dimming system covering the 15 to 20 feet from the outer wall of a highly fenestrated open office space.

- Presence detection in warehouse requiring two levels of illumination.

- Small control zones in large open office.

3. CONTROL SYSTEMS

3. CONTROL SYSTEMS

3.1 ENERGY AND INFORMATION FLOW

3.1.1 General

The control system diagram, Figure 2-1, identified three major flow paths: electrical energy, control information, and light energy. The flow of light energy is part of Lighting System design and is beyond the scope of this Handbook. Each of the other flow paths can be treated almost independently of the other as long as the interface between the two is accounted for.

3.1.2 Electrical Energy Flow

The flow of electrical energy is from the building electrical service to the Controlled Element (ballast and/or lamp). Between these two end items will be various protective devices (fuses, circuit breakers) and a means to turn the Lighting System ON and OFF (whether or not the System is dimmable or not). There are four possible controls for the electrical energy: circuit breaker, switch, relay or contactor, and they are shown schematically in Figure 3-1. In Figure 3-1a, a circuit breaker is used to control an entire circuit consisting of one or more Controlled Elements. Control of this circuit is Manual. In Figure 3-1b, a switch is used to control one or more Controlled Elements and more than one switch can be on the same circuit. Control of this circuit is Manual.

The possibility of remote or automatic control is indicated in Figures 3-1c and 3-1d where a Control input is indicated to the Control Device. In Figure 3-1c, a relay contact has been substituted for the switch in Figure 3-1b. There is no other difference except that the means of turning the Controlled Element ON and OFF is accomplished with an electrical signal rather than by manual operation. The electrical control signal may be generated in a manual switch or in an automatic Decision Element.

The relay as shown is used to control a single circuit or a part of a circuit. Additional contacts on the same relay can be used to control other Controlled Elements. Where control of a large block of lighting is desired, a contactor is used ahead of a panelboard to control power to all of the circuits supplied by the panelboard. Figure 3-1d shows the location of one phase contact of a contactor. In general, contactors are equipped with two power contacts for single phase 120/240 volt service and three power contacts for three

phase 480Y/277 volt service. In either case, a single set of
control signals will close and open all contacts together.
The branch circuit wiring on the load (downstream) side of the
contactor is similar to the wiring for circuit breaker
control shown in Figure 3-1a.

For dimming control, there are two basic systems to be
considered: reduced voltage and dimming ballast. Figure 3-
2a shows a manual dimmer in place of the switch control of
Figure 3-1b. The wiring is the same, only the Control Device
has been changed. For remote or automatic control, a control
voltage operated dimmer with a relay is shown in Figure 3-2b
and the Control Device is a direct replacement for the relay
shown in Figure 3-1c. Reduced voltage dimmers which provide
a continuous dimming range from 0 to 100 percent (thereby
providing an OFF position) are generally not equipped with
the relay shown. Otherwise, the circuitry is the same.

When a dimming ballast is used, the ballast has a dual
function. The ballast provides the proper voltage for the
lamp and is, therefore, part of the Controlled Element. In
addition, the ballast provides the mechanism by which power
can be reduced to the Controlled Element and so it is also a
Control Device. Wiring of the dimming ballast is shown in
Figure 3-2c. It is seen to be similar to the remote reduced
voltage control of Figure 3-2b except that there is no
possibility of adding additional Controlled Elements without
addition of the corresponding Control Device function.

The wiring configuration for control of electrical
energy flow can be seen to be relatively independent of the
control method and more dependent upon the physical size
(electrically) of the individual control zones.

3.1.3   Control Information Flow

In automatic systems, control information flows from
the Sensor to the Control Device. Between these two end items
is the Decision Element which may be a part of the Sensor
package or it may be separate. There are three basic con-
figurations for information flow consideration:

a.   Integrated Sensor package for ON-OFF or dimming
     control.

b.   Separate Decision Element for ON-OFF or dimming
     control.

c.   Sensor/Decision Element/Control Device proprietary
     system for dimming control.

-45-

CONTROL DEVICE

CONTROLLED ELEMENT
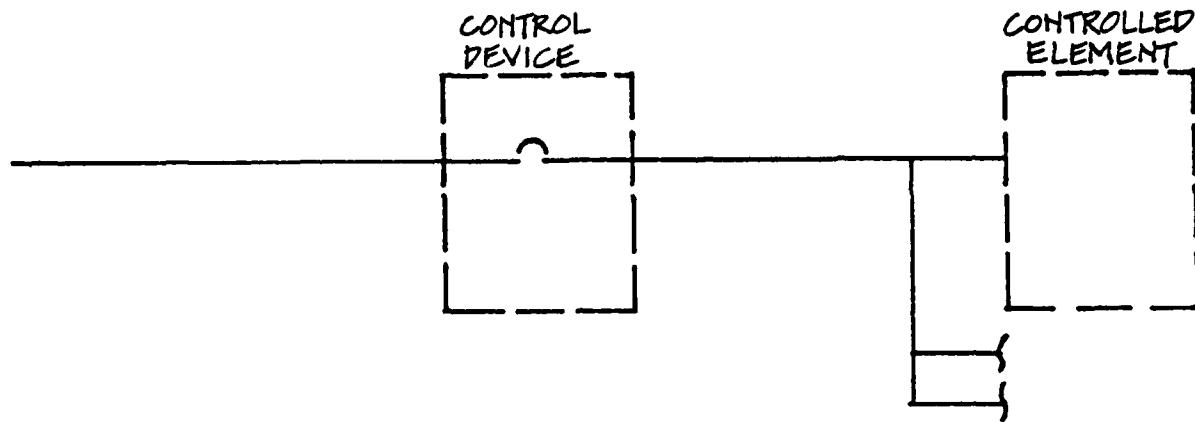
A. CIRCUIT BREAKER CONTROL
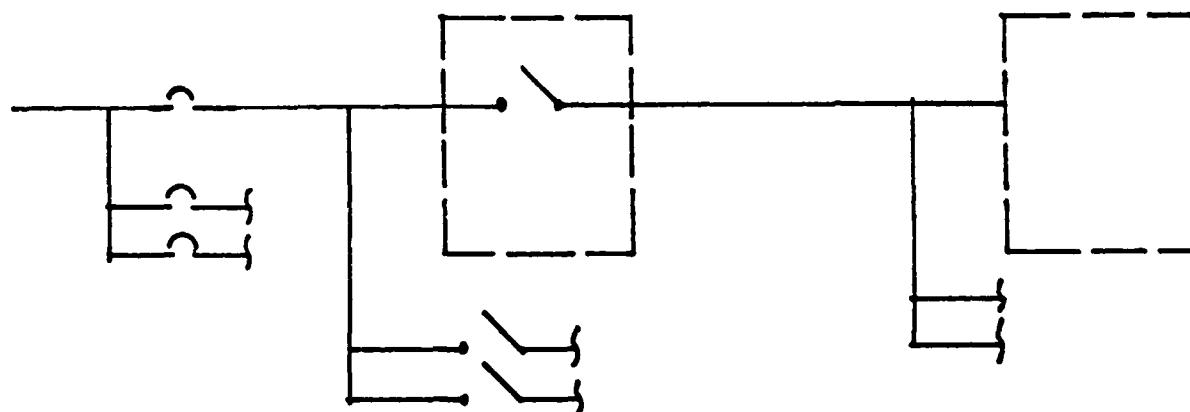
B. SWITCH CONTROL
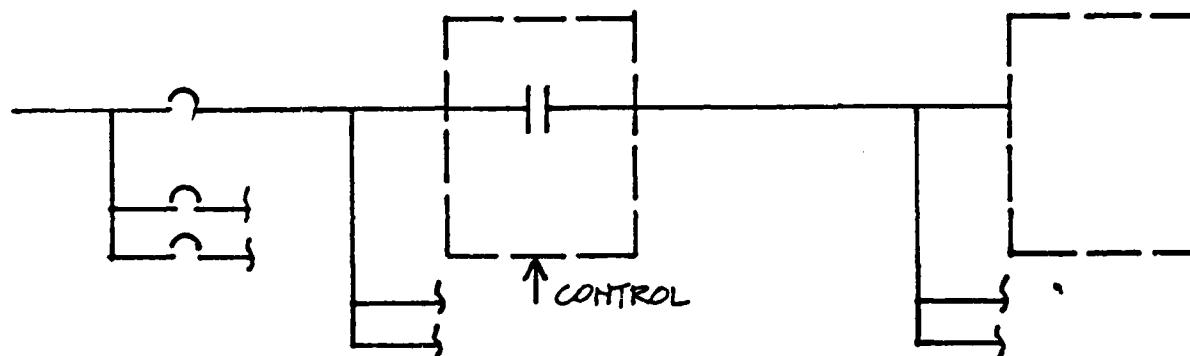
C. RELAY CONTROL
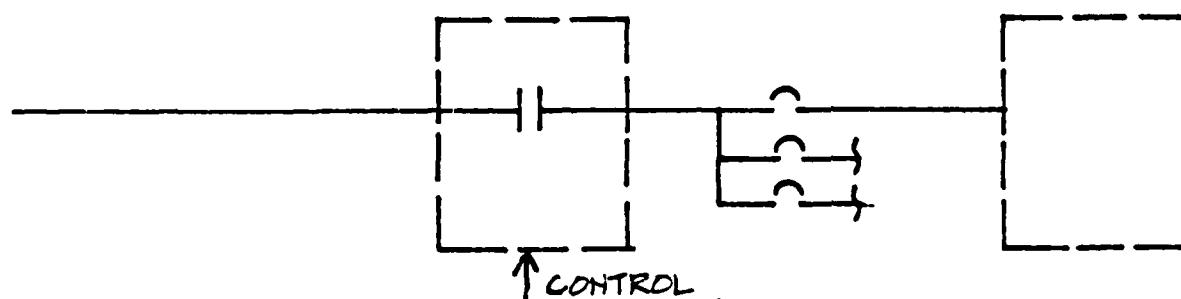
CONTROL

D. CONTACTOR CONTROL OF PANELBOARD

CONTROL

ON-OFF CONTROL OF ELECTRICAL ENERGY

FIGURE 3-1

-46-

CONTROL DEVICE

CONTROL ELEMENT

DIMMER
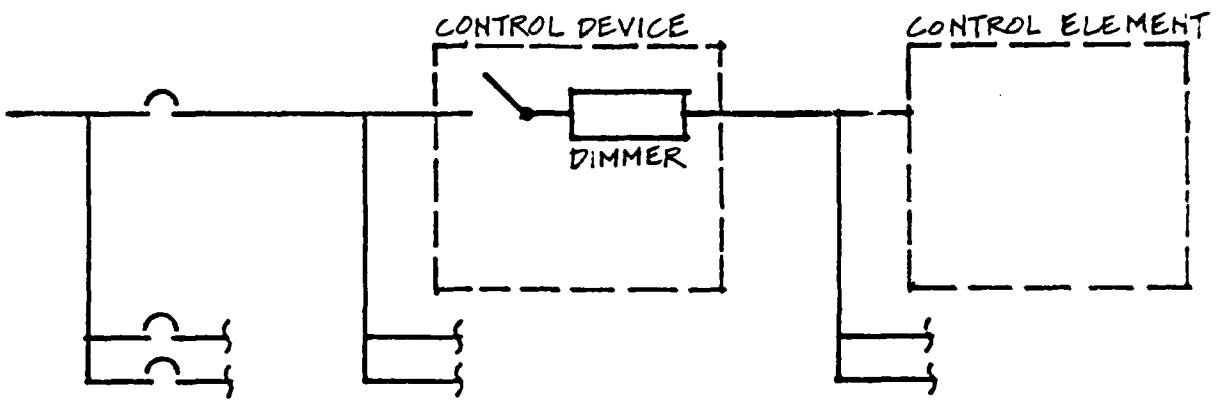
A. MANUALLY REDUCED VOLTAGE CONTROL

(OPTIONAL) DIMMER
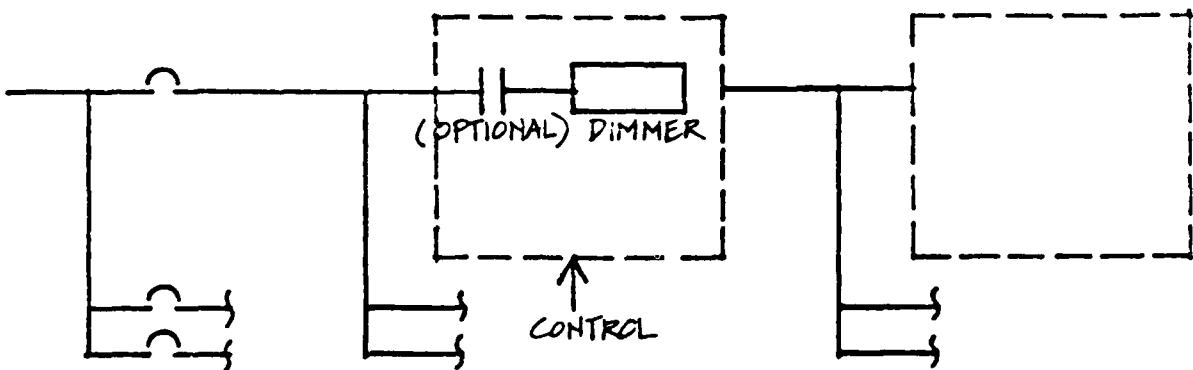
CONTROL

B. REMOTE OR AUTOMATIC REDUCED VOLTAGE CONTROL

CONTROL DEVICE

CONTROLLED ELEMENT

(OPTIONAL)

DIMMING BALLAST
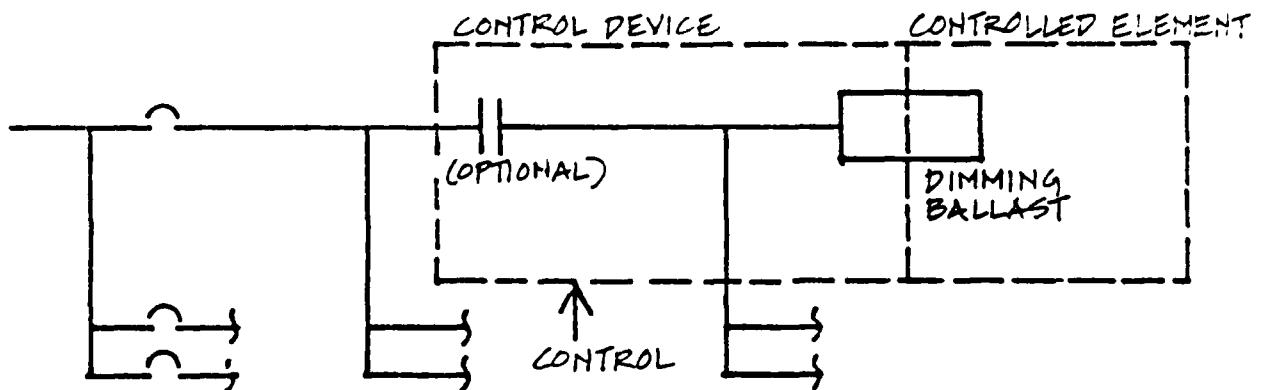
CONTROL

C. REMOTE OR AUTOMATIC DIMMING BALLAST CONTROL

DIMMING CONTROL OF ELECTRICAL ENERGY
FIGURE 3.2

Integrated Sensor packages include timers, time clocks, photoelectric devices and presence detectors that have an output contact closure (relay contact or switch) or analog output voltage (dimmer) when the measured parameter (time, illumination, or presence) reaches a desired condition. The Sensor output may be the Control Device if its electrical rating is compatible with the Controlled Element requirements. If the ratings are not compatible, then the Sensor output may operate a Control Device whose output rating is compatible with the Controlled Element. The interconnection between Sensor and Control Device (or Controlled Element if operated directly) is simply a pair of insulated electrical conductors. Depending upon the operating voltage and the routing of the conductors, they may or may not be installed in conduit in accordance with the National Electrical Code. It is important to note that the interconnection is typically between two devices that are not part of an integrated system, but are purchased separately. Compatibility of the devices is a responsibility of the control system designer.

A separate Decision Element usually implies a programmable controller, microprocessor, or a computer. These Decision Elements are digital devices that receive and transmit information by the absence or presence of a signal (voltage) rather than the absolute value (voltage) of that signal. (See Section 2.3.) A Sensor that has a contact closure for an output is digital in form and can be connected directly to the Decision Element with a pair of conductors. The output of the Decision Element is a contact closure that can be used to operate the Control Device through a pair of conductors. The connection of the three components is shown in Figure 3-3b.

If the Sensor has an analog output, such as a photocell that measures illuminance, it may be desirable to transmit the absolute value of illuminance to the Decision Element for processing. Since solid-state Decision Elements can only process digital information, it is necessary to convert the Sensor analog signal to digital data by means of an analog to digital (A/D) convertor. Because digital transmission of information is least susceptible to loss of information, it is most desirable to locate the A/D convertor close to the Sensor.

The connection between A/D convertor and the solid-state Decision Element is by means of a shielded twisted pair cable. This cable is used in two directions; first by the Decision Element to tell the A/D convertor that it is ready to receive information, and then by the A/D convertor to transmit the present value of the analog input. Because the Decision Element can address a specific A/D convertor, it is
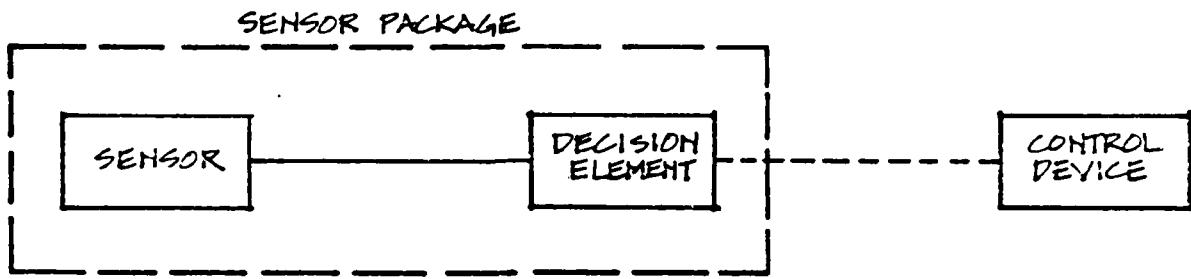
SENSOR PACKAGE

A. INTEGRATED SENSOR PACKAGE

B. SEPARATE DECISION ELEMENT WITH DIGITAL INPUT/OUTPUT
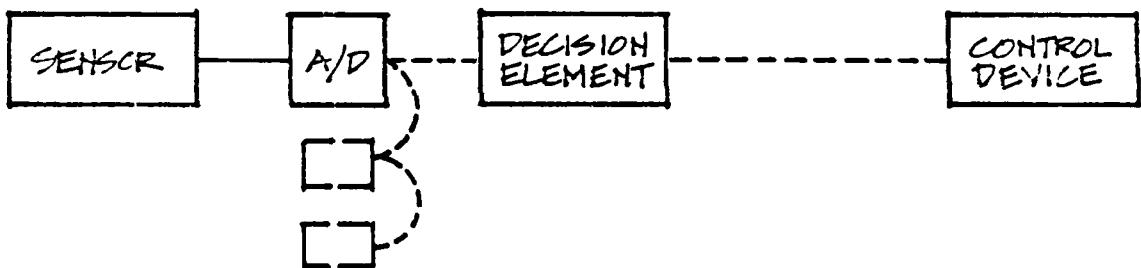
C. SEPARATE DECISION ELEMENT WITH ANALOG SENSOR

D. SEPARATE DECISION ELEMENT WITH ANALOG SENSOR AND CONTROL DEVICE

ANALOG _____   DIGITAL _ _ _ _ _ _ _

CONTROL INFORMATION FLOW
FIGURE 3-3

possible to connect several devices onto the same shielded twisted pair cable. The analog and digital connections are shown in Figure 3-3c.

For dimming purposes it is necessary for the Decision Element to transmit analog information to the Control Device. Since the Decision Element has only digital outputs, it is necessary to convert to analog by means of a digital to analog (D/A) convertor. For reliability of signal transmission, the D/A convertor should be as close to the Control Device as possible. In operation, the solid-state Decision Element addresses the D/A convertor first and then sends the digital signal in serial form. Because the D/A convertor is addressed first before receiving information and the A/D convertor is addressed first before sending information, it is generally possible to have several of each type of convertors connected to the same shielded twisted pair cable. (See Figure 3-3d.) It can be seen that economies of wiring installation may be achieved using digital transmission of control information. The number of devices on a single line and the ability to mix input and output devices depends upon the specific manu-facturer. It is also important to note that care must be taken that each device is compatible with the input and output of the devices to which it is connected.

There are proprietary control systems that include the Sensor, Decision Element and Control Device and they are typically used for dimming control. With this type of system, compatibility of components is warranted by the manufacturer and the interconnection cable is part of the system. In principle, it is not important what the internal signal transmission method is, whether digital or analog, as long as the components work together as a system. If, however, the recommended wiring method results in excessive installation costs, then other systems of signal transmission should be considered.

3.2   MANUAL CONTROL

3.2.1   General

In Manual Control, sensing of the existing illumination level (Sensor function) and making the decision to turn lights ON or OFF or dim them (Decision function) is performed by a human; therefore, the manual circuits that follow consist only of a Control Device and a Controlled Device.

3.2.2   Panel Control

The simplest form of lighting control is to operate all lights that are connected to the same circuit as a single control zone. Figure 3-4 shows a wiring diagram for this arrangement. In order to accomplish control, it is necessary that the branch circuit panelboard have a separate disconnecting means for each circuit (control zone).

Circuit breakers provide both overcurrent protection and a disconnecting means. In order to be used on a daily basis as a switch to turn lights ON and OFF, it is necessary that the circuit breaker be designed for that purpose since circuit breakers, in general, are designed to be closed and left closed until a fault occurs. Circuit breakers designated "SWD" are designed, tested, and listed for use as switching devices, and are required by the National Electrical Code to be used when circuit breakers are used as switches (see National Electrical Code Article 240). As of January 1983, "SWD" designated circuit breakers were available and listed for voltages up to 250 volts and for 15 and 20 ampere current rating. It may be concluded that panel switching for 277 volt circuits is not permitted by the National Electrical Code until appropriately rated and listed devices become available.

Fused branch circuit panelboards are generally available for a maximum of 250 volts and may be provided with switches. The use of fused panelboards is rare because of the inconvenience of keeping a supply of each fuse current rating used in the panelboard.

3.2.3   Local Switching

Probably the most familiar form of Manual Control is the local wall switch used at the entrance to a small space. The wall switch may be at the doorway to a one- or two-person office, a closet, a mechanical room, a utility room, etc. Also included in this grouping is the individual switch installed on the luminaire such as a floor or table lamp or a task light. A combined schematic and wiring diagram, Figure 3-5, shows how multiple lights are connected to the same

4 WIRE
208Y/120 VOLT

NEUTRAL

CONTROL
ZONE 1
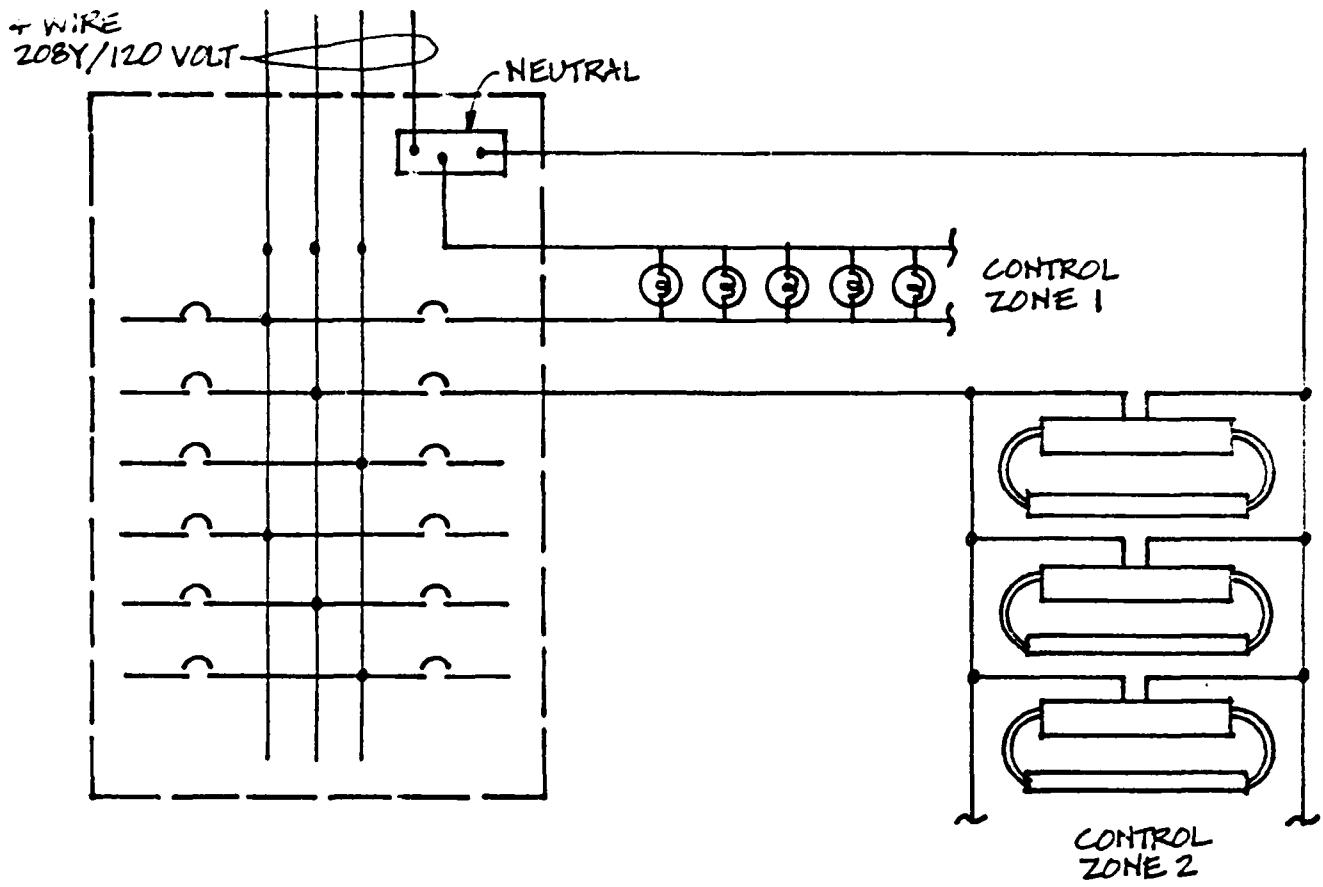
CONTROL
ZONE 2

PANEL CONTROL OF LIGHTING
FIGURE 3.4

FROM
BRANCH
CIRCUIT
PAHEL-
BOARD

ø

N

NO NEUTRAL
IN THIS BOX
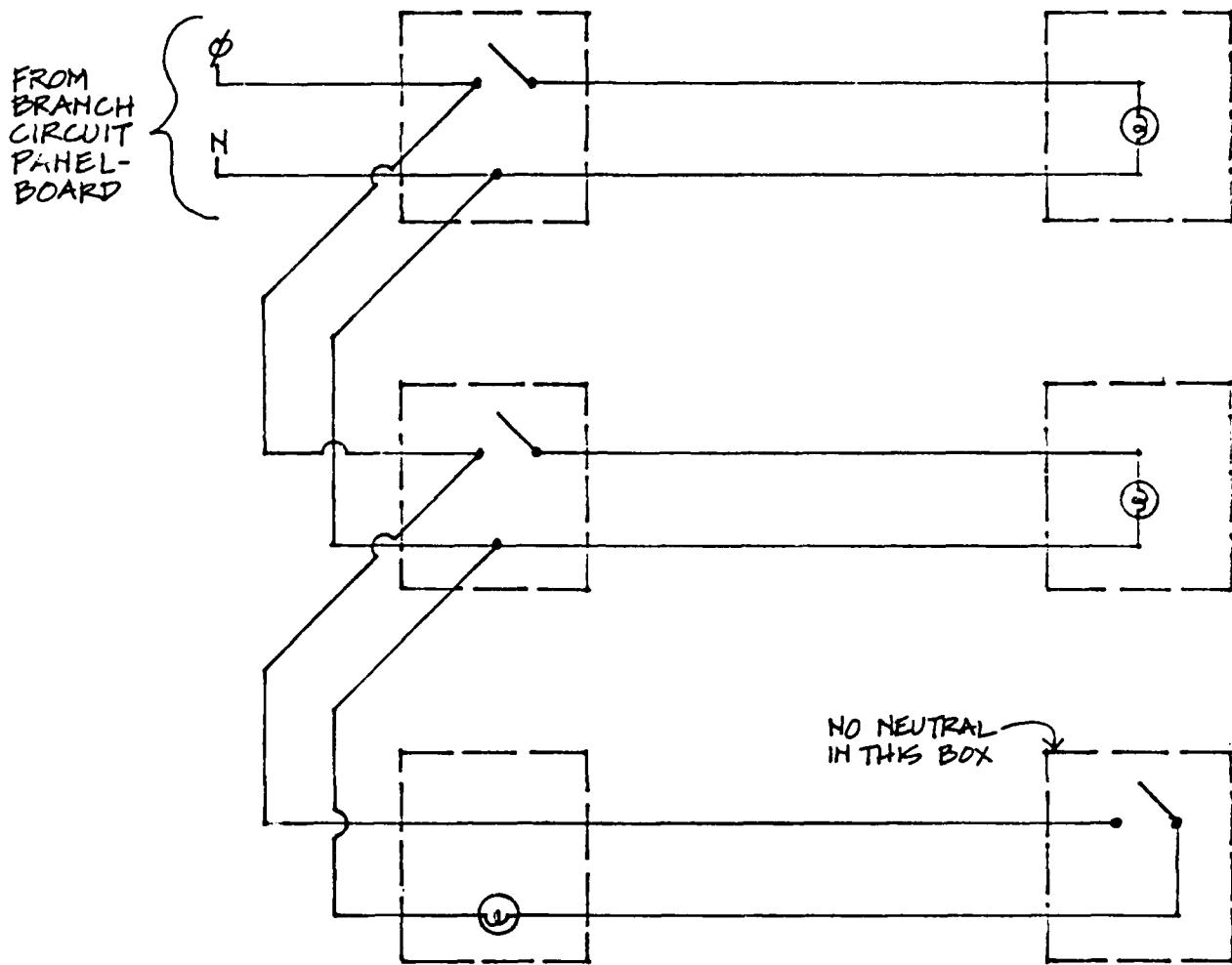
MANUAL CONTROL FROM ONE LOCATION
FIGURE 3.5

circuit and the wiring differences when power is brought into the switch or into the lighting fixture. Note, in Figure 3-5, that when power is brought directly into the lighting fixture, there is no neutral conductor at the switch. This fact may be important when upgrading existing controls that involve the replacement of existing switches with electronic devices that require a neutral conductor.

Where it is desired to control lighting from two locations such as two entrances to a classroom or both ends of a hallway or stairwell, two three-way switches can be used. For more than two control locations, three-way switches are used at the ends of the control circuit and as many four-way switches as required are used. Figure 3-6 shows the wiring for three different physical arrangements of control from two locations and Figure 3-7 shows two wiring arrangements for control from three or more locations.

3.2.4 Local Switch with Relay

Many of the physical limitations of the previous Manual Control circuits can be overcome by the use of some form of relay between the branch circuit and the luminaire. Some of the functions that can be obtained are:

- Simplified multi-location wiring.

- Central control of multiple circuits.

- Operation of large blocks of lighting.

- Portable or remote switch.

3.2.4.1 Low Voltage Switching

The low voltage relay is an electrically operated, mechanically latched relay that simplifies multi-location wiring in at least four ways:

- Low voltage wiring can be used.

- Cable listed for use in a ceiling air plenum without conduit is available.

- Additional control locations for a given luminaire group can be added relatively independent of previous control wiring.

- Master operation of many groups of luminaires can be easily added.

BRANCH CIRCUIT — φ — N

3-WAY SWITCH

3-WAY SWITCH

LUMINAIRE

BRANCH CIRCUIT — φ — N

3 CONDUCTORS

LUMINAIRE

BRANCH CIRCUIT φ N

3-WAY SWITCH

LUMINAIRE

3 CONDUCTORS

3-WAY SWITCH
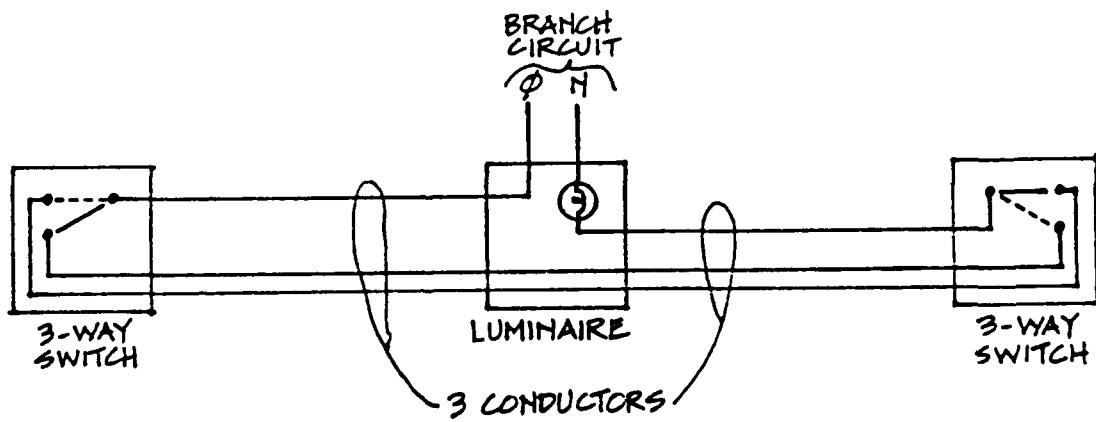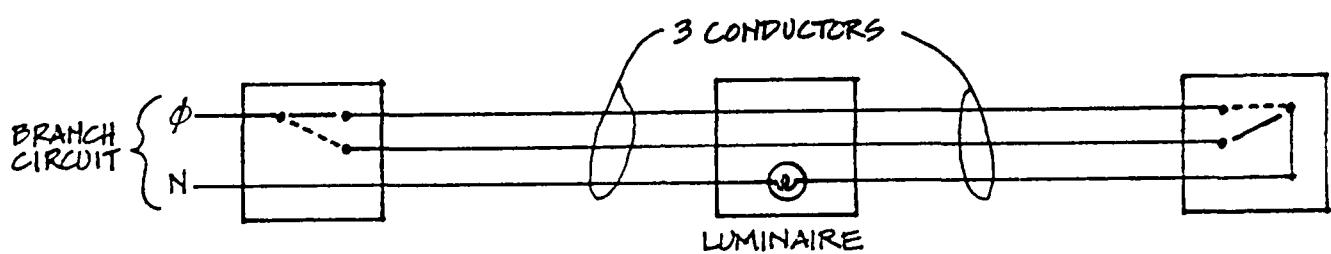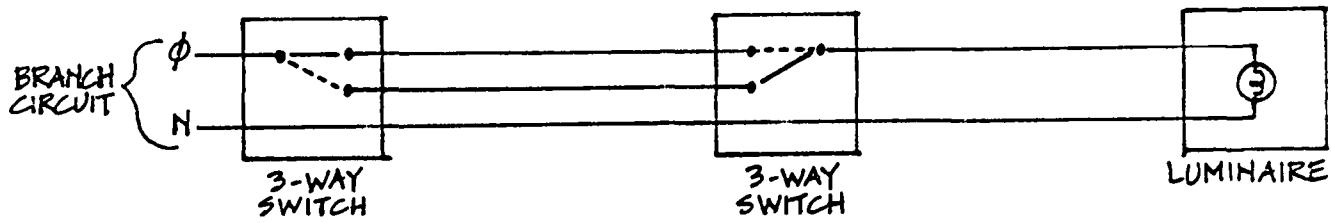
MANUAL CONTROL FROM TWO LOCATIONS
FIGURE 3.6
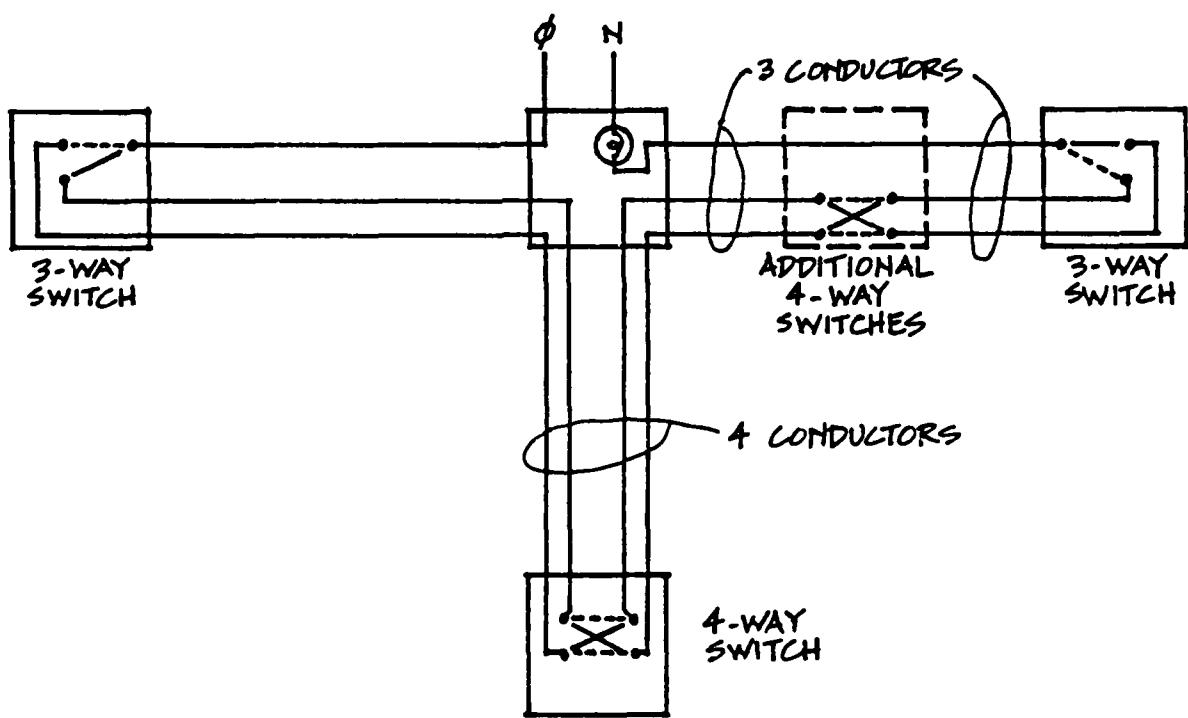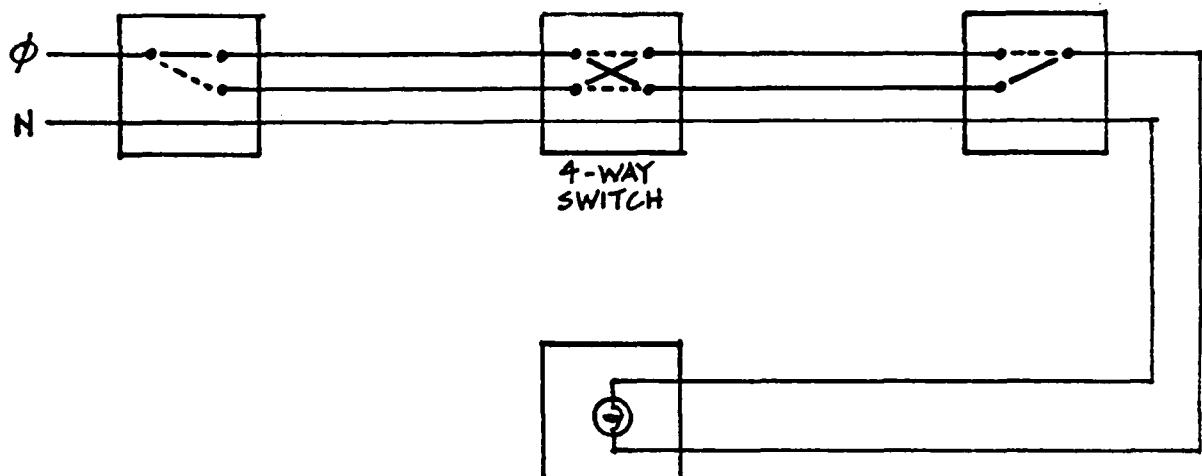
MANUAL CONTROL FROM THREE OR MORE LOCATIONS
FIGURE 3.7

The relay typically consists of two electrically isolated parts. The output portion is a single pole switch rated for 20 amperes at either 120 volts or 277 volts. No three-way switches are available as they are not necessary in this system. The input portion consists of two low voltage (typically 24 volt) coils, one of which will close the output switch and the second will open the output switch. The output switch is always latched so that loss of voltage, either on the input or the output, will not change the state of the output switch. A positive signal to the appropriate input coil for a sufficiently long period (typically 60 milliseconds) is necessary to change the state of the output switch.

The typical control station consists of a single pole, double throw, momentary contact switch. Each position of the switch operates one of the two relay coils. Other momentary contact switches could be used. The duration of contact closure should be kept short to prevent relay overheating, and to prevent interference with other control operations. See manufacturers specifications for limitations.

A wiring diagram for low voltage control of a control zone consisting of a single luminaire or a group of luminaires is shown in Figure 3-8. One relay is used for the zone. If the control zone is large, requiring more than one branch circuit, then one relay per circuit could be used with the relays connected in parallel operated from the indicated control diagram. Wiring of the luminaires is as shown in Figure 3-5, Manual Control from One Location, where the relay output switch is substituted for the single pole switch. In Figure 3-8 note that the paralleling of the momentary switches can occur at the relay, at a switch location, or at an intermediate location. Note also the single pole, single throw switch connected to turn lights OFF only. Three conductor cable, as indicated, is used wherever both ON and OFF functions are required and two conductor cable is used for power and for single functions.

For Master Control of more than one group of luminaires from one or more locations, it is necessary to use diodes to prevent the local control of one circuit from operating a second circuit. The wiring diagram shown in Figure 3-9 shows one possible arrangement of master control and diodes. The single diode located at the 24 volt control voltage source is not necessary for proper logic operation, but is recommended by the manufacturer for more positive operation of the relays.

The diodes of the previous circuit are necessary only because there is a single momentary contact switch to turn all circuits ON and OFF at the same instant of time. Where it is permissible to sequentially operate all circuits in a short

120V.
OR
277V.

N

ϕ

TO LUMINAIRE(S)

OPEN   CLOSE

LOW VOLTAGE RELAY

2C

120V.
OR
277V.

24 VOLT
TRANSFORMER

2C

2C

OFF

3C

OFF   ON

3C

OFF   ON

OFF   ON

3C
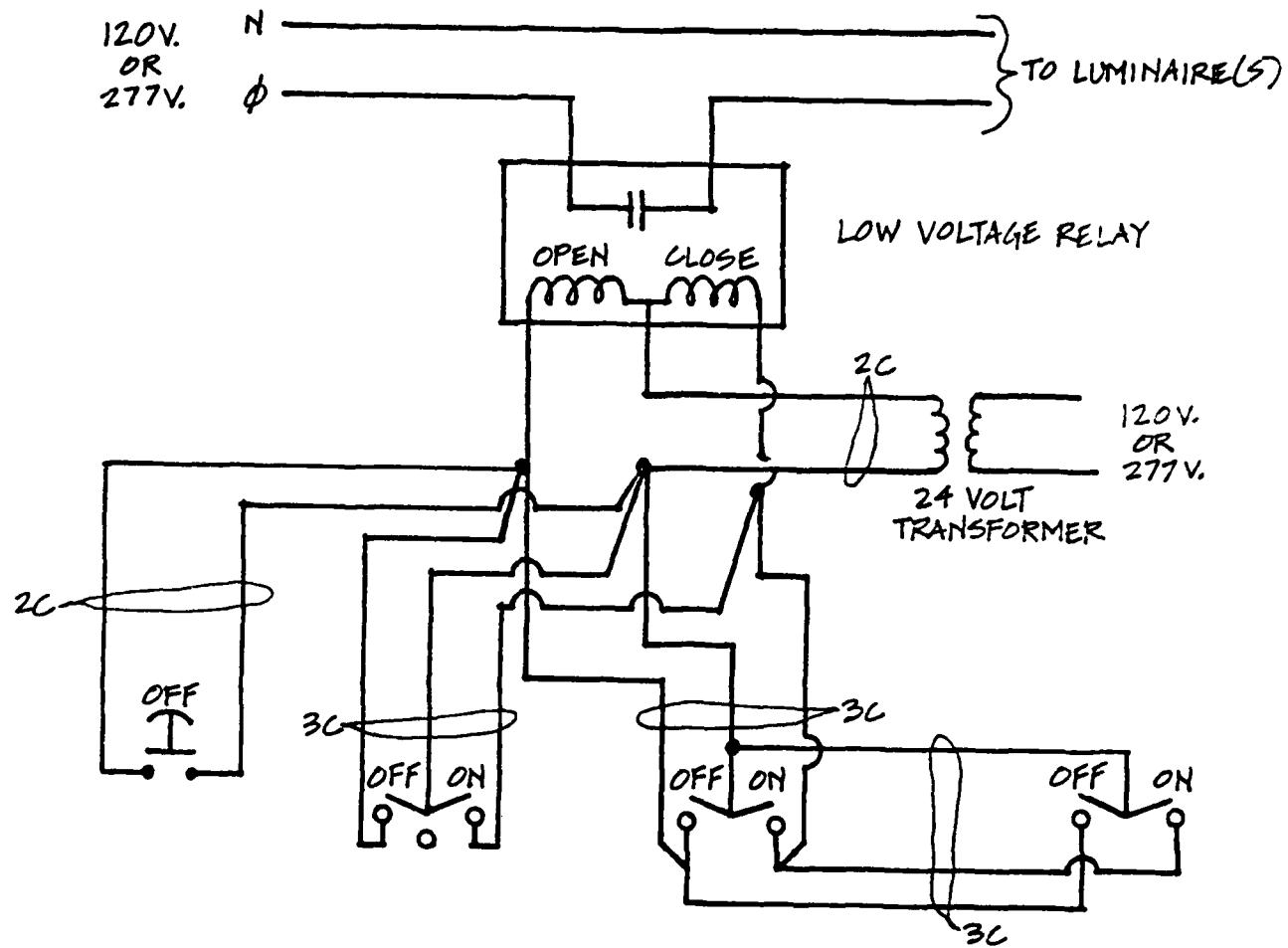
LOW VOLTAGE CONTROL OF LUMINAIRE (S)
FIGURE 3.8
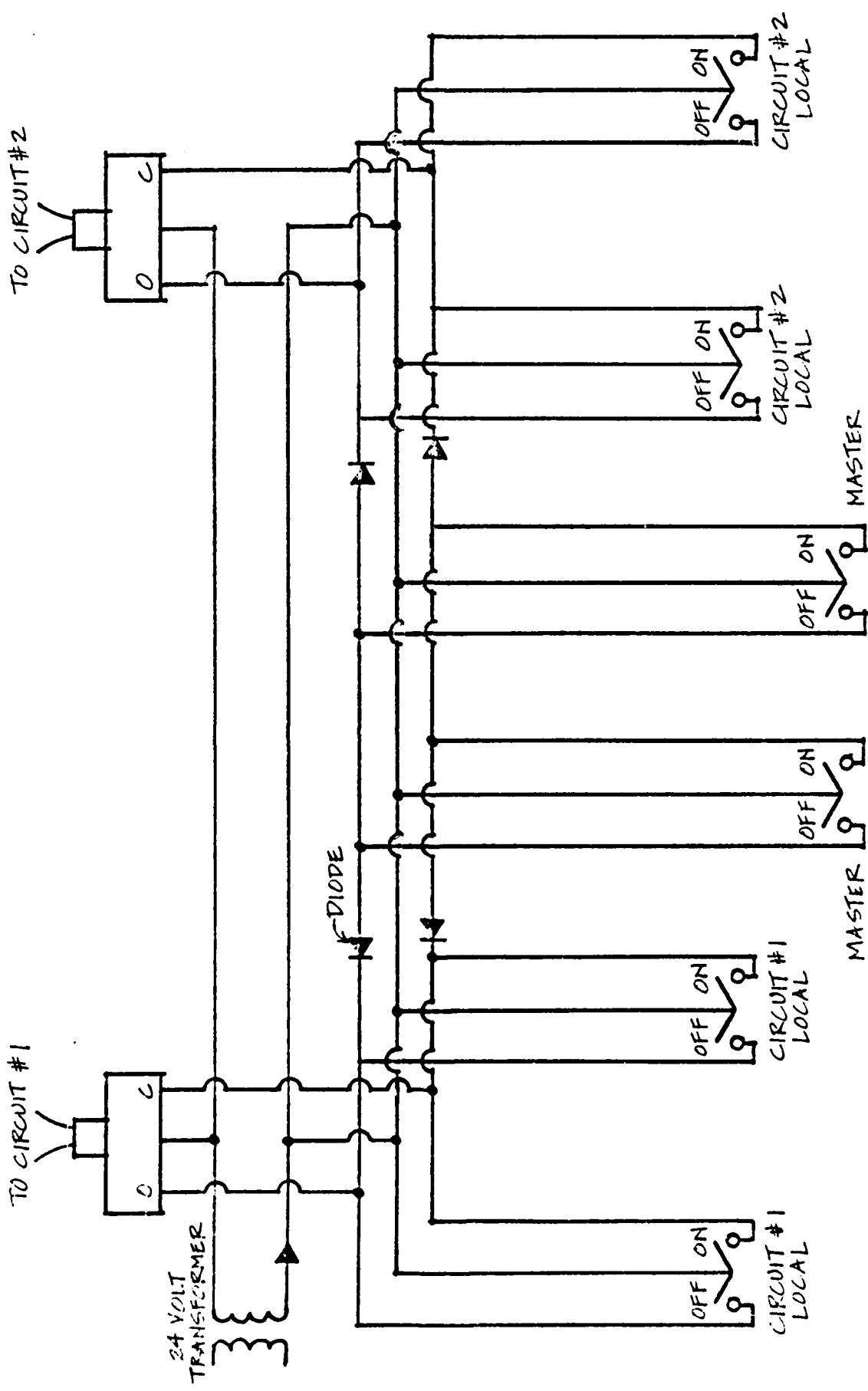
LOCAL AND MASTER CONTROL OF TWO GROUPS OF LUMINAIRES

FIGURE 3.9

period of time, a stepping switch is available. A partial wiring diagram for a master stepper control is shown in Figure 3-10. The stepping switch can be considered as a series of individual local switches that are sequentially operated by mechanical means following a single command pulse. The single Master Control switch is appropriate where changes of lighting are more effective if accomplished instantaneously. The stepping switch is often appropriate for energy management systems where all lights are turned OFF by time clock and ON by the occupants of the space (lighting zone). It should be noted that the command signal to the stepping motor must be a pulse. Time clocks are available with short pulse outputs. Electronic means are available to provide a pulse from a continuous output. Refer Section 3.5.

3.2.4.2 Contactor Control

For operation of large blocks of lighting such as in an open office plan or in a warehouse or plant, a contactor permits many circuits to be operated from a single switch. The contactor, as described previously in Section 2.4.3, has two separate ratings--one for the control circuit and one for the power circuit.

The power circuit may be used in one of two ways--three pole contactor may be used to control the power to a branch circuit distribution panel, which in turn feeds lighting circuits; or a multipole contactor (one for each lighting circuit) may be connected after the branch circuit protection. The two methods are shown in Figure 3-11. Note that the multipole contactor is similar to using several single pole relays and connecting their operating coils in parallel.

The power contacts may be rated for 208Y/120 volts or for 480Y/277 volts either single phase or three phase. Three pole contactors are generally available with ratings as high as 1,200 amperes and the multiple pole contactor is usually rated from 20 to 50 amperes with up to 12 poles.

The control circuit is considered separately and is independent of the indicated power circuit. There is electrical isolation between the power circuit and the control circuit so that the control voltage can be independently specified. A description of "electrical holding" and "mechanical latching" of the contactor armature and the use of coil clearing contacts is included in Section 2.4.3 and shown in Figure 2-3. Note that a control switch from a Sensor, Decision Element, or local manual station can operate the contactor.
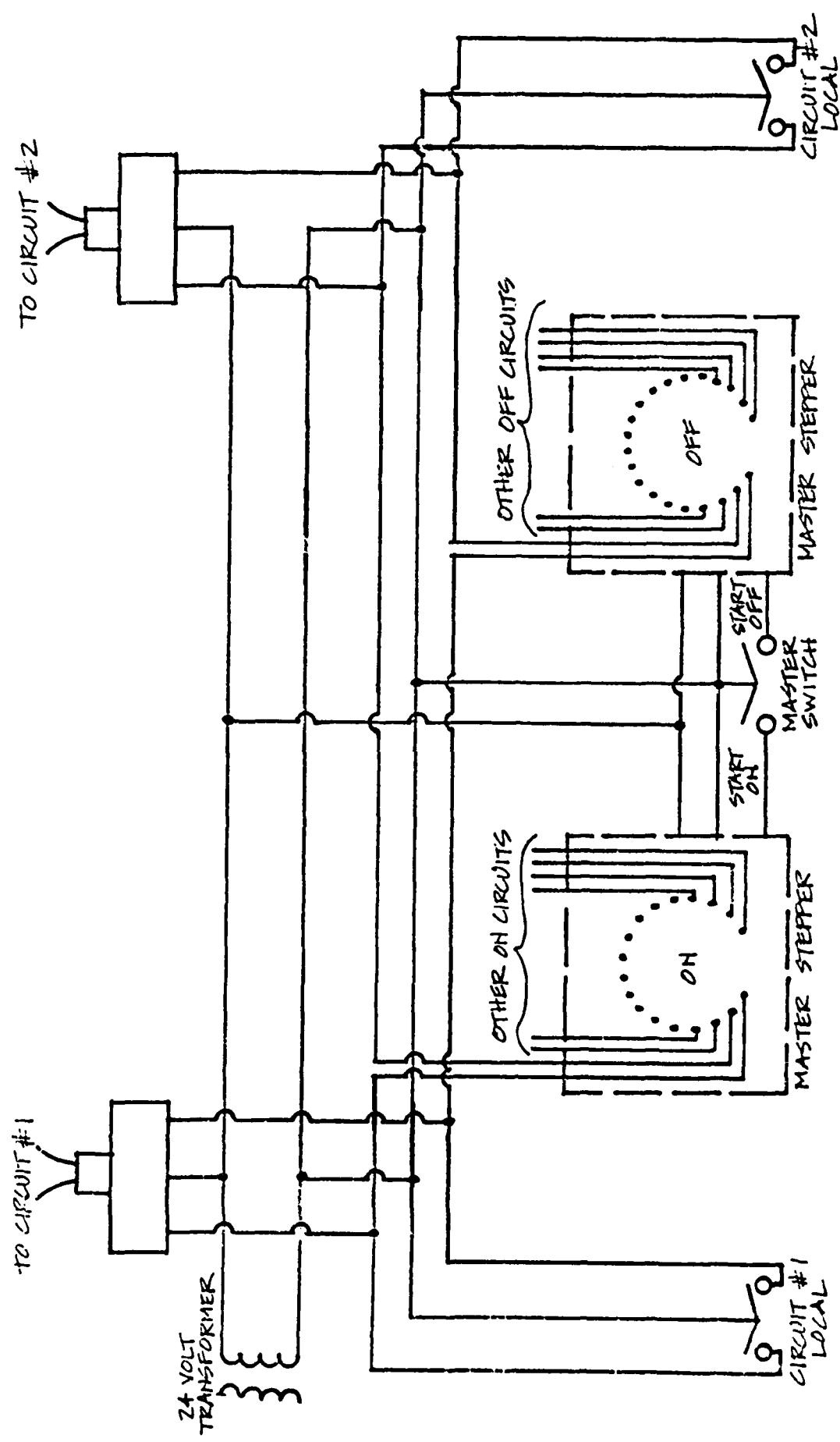
MASTER CONTROL USING STEPPER MOTORS
FIGURE 3.10

CONTACTOR

BRANCH CIRCUIT PANELBOARD (NEUTRAL NOT SHOWN)

FEEDER PANELBOARD

TO LIGHTING CIRCUITS

TO LIGHTING CIRCUITS

A. PANELBOARD CONTROL

TO LIGHTING CIRCUITS

6-CIRCUIT CONTACTOR

BRANCH CIRCUIT PANELBOARD (NEUTRAL NOT SHOWN)
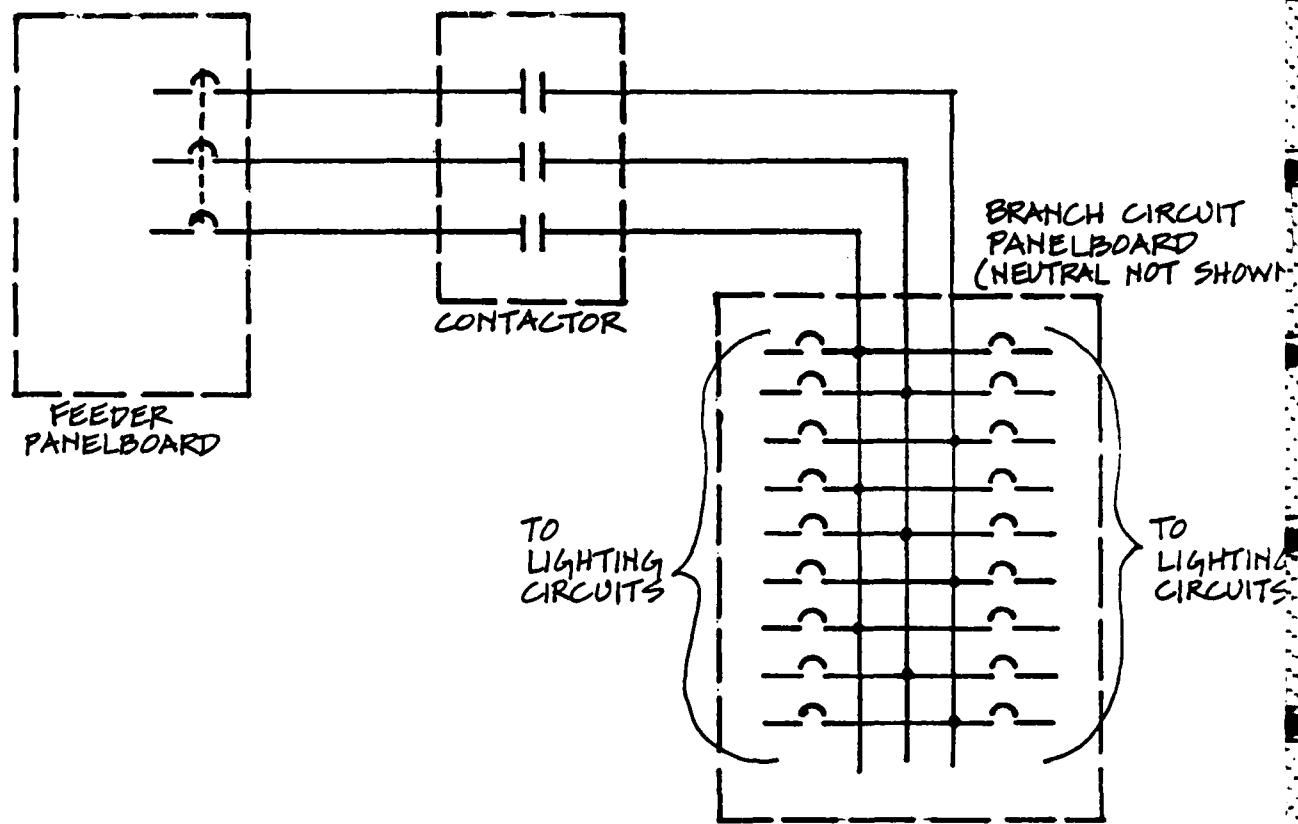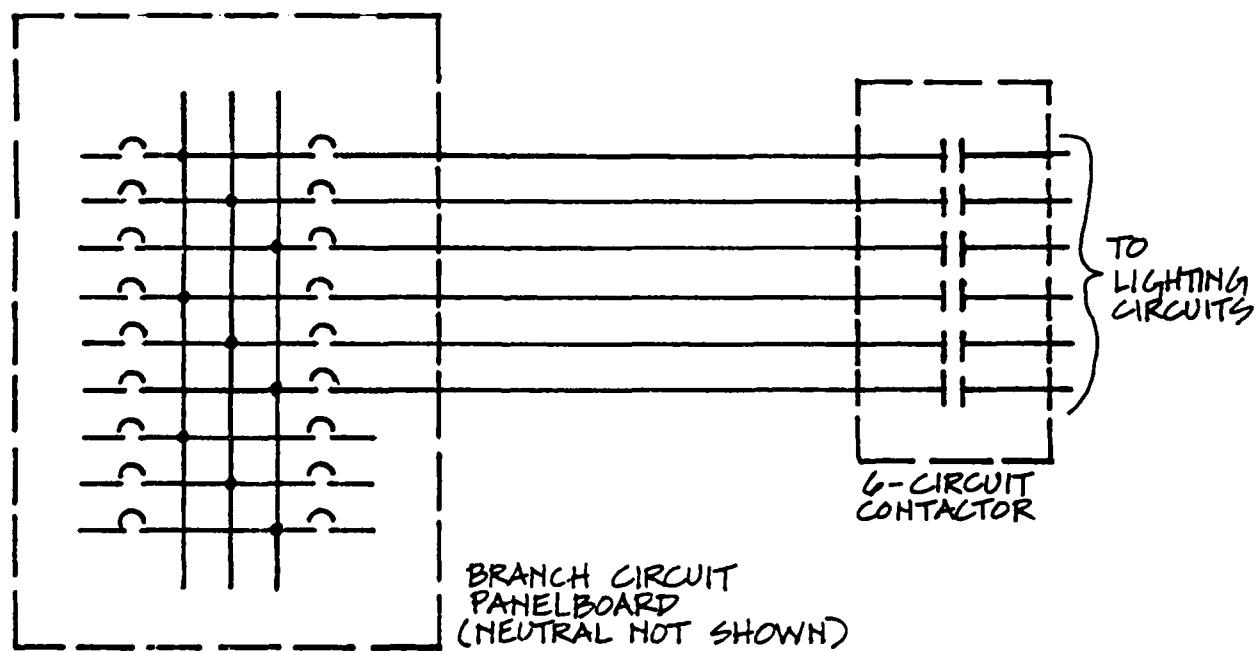
B. BRANCH CIRCUIT CONTROL

CONTACTOR CONTROL OF MULTIPLE LIGHTING CIRCUITS
FIGURE 3.11

3.2.4.3   Portable Switch

The portable switch consists of a transmitter which is portable and a receiver that is installed in place of a fixed local switch.   The transmitter/receiver pair operates on sonic energy or on infrared energy. Most remotely operated TV and video recorders used infrared transmitters which are directional (line of sight). The sonic transmitter/receiver is non-directional.   The transmitter either requires no electrical power or battery power to operate. A wiring diagram for the receiver is shown in Figure 3-12.   The receiver requires both phase and neutral conductors. Because of the need for a neutral conductor, the receiver switch cannot be substituted in all cases for an existing switch. See the lower diagram in Figure 3-5, Manual Control from One Location. Otherwise, this switch is similar in use to any manually operated switch. This equipment has been found useful in a laboratory environment where room ambient lighting was required for set up, but the operator could not move from his work place to dim or turn OFF the ambient lighting. The portable transmitter permitted him to operate the lighting.

The control system designer should be particularly careful about using equipment with Underwriters Laboratories or other testing laboratory listing for the intended use. This is particularly true of "new" technology items intended for other applications but adapted for use in systems governed by the National Electrical Code.

3.2.4.4   Carrier Controller Switch

A carrier controlled switch uses the existing building wiring system to provide a signal path between a manually controlled switch (transmitter) and a Control Device (receiver) at the Controlled Element location. The transmitter sends a series of high frequency carrier signals (typically above 100 mega hertz) whenever the switch is operated. The carrier is superimposed on the normal 60 hertz system. If the high frequency signal is of low enough magnitude (typically 5 volts) and if it is transmitted at the zero crossing of the 60 hertz building supply, then the carrier will be easy to detect and will not interfere with the operation of other electronic equipment.

The transmitter is typically coded and may be programmed to transmit one of 256 different codes (a specific manufacturer's product). The code is transmitted by first sending a start signal consisting of a sequence of high frequency bursts (binary "1") or no high frequency bursts (binary "0") at successive zero crossings. Following the start signal, a series of bursts and/or no burst of high frequency at successive zero crossings identify the

-63-

RADIANT ENERGY

RECEIVER

φ

N
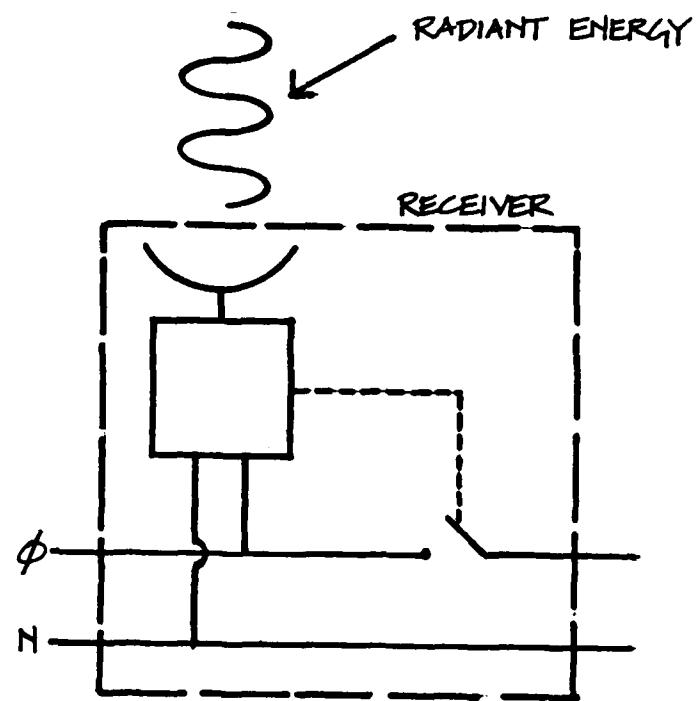
RECEIVER SWITCH FOR
PORTABLE TRANSMITTER
FIGURE 3.12

specific one out of 256 possible combinations. The high frequency signals when superimposed on a single branch circuit will appear on all branch circuits connected to the same phase of the system transformer. By adding a simple coupling device at the system transformer or panelboard, the high frequency signal will appear on all branch circuits of the same system transformer.

The receiver is a switch that is activated when a specific coded series of high frequency bursts is detected. The receiver can be programmed to respond to one of 256 different codes. It is, therefore, possible to have one transmitter operate many receivers or many switches operate one or many receivers. Since the control signal appears on all branch circuits, transmitters and receivers can be installed almost any place within a building.

3.2.5   Incandescent Dimmer Control

Incandescent lamps (Controlled Element) which operate at line voltage can be dimmed by reducing the applied voltage to the lamp. The compact solid-state thyristor dimmer described in Section 2.4.5 provides the most commonly acceptable means to reduce the effective (r.m.s.) value of voltage by controlling the phase angle of the input voltage sine wave at which an output voltage begins. The dimmer is a three terminal device having an input voltage connection, an output load connection, and a neutral connection.

Low voltage incandescent lamps which operate generally at 6 or 12 volts include a transformer as a part of the Controlled Element. Dimming is generally accomplished by a reduction to the primary voltage of the transformer. When using thyristor based dimmers, the inductive load should be considered and dimmers rated and listed for this type of load must be used. Otherwise, connection, use, and available types are similar to line voltage incandescent systems.

Incandescent dimmer control is capable of providing a continuous, flicker-free range of illumination from 0 percent to 100 percent, whether the system is line voltage or low voltage.

There are two general types of dimmers to be considered: low power and high power. The low power dimmer (up to 2,000 watts) is designed to be installed in a wall box and, for retrofit, can be used in place of a wall switch. It is nearly always a thyristor dimmer. Connection of the dimmer for manual control from one or more locations is as shown in Figures 3-5, 3-6 and 3-7 with the two wire dimmer replacing a single pole switch or a three wire dimmer replacing one of the three-way switches. It is generally advisable to install

a debuzzing coil between the dimmer and the lamp to limit RFI and lamp singing as described in Section 2.4.5, if the coil is not integral to the dimmer.

For high power (from 2 kW to more than 100 kW), large high capacity remote dimmers or multiple smaller capacity dimmers that can be controlled from a common command unit (potentiometer) are used. High power thyristor dimmers should always utilize SCR circuitry. Each dimmer supplies electrical energy to its own load independent of other dimmers. If the load supplied by a dimmer exceeds the capacity of a single circuit, then the dimmer must be equipped with overcurrent protection for each load circuit. The power connection of several dimmers on a single phase circuit is shown in Figure 3-13. Note that each load is independent of the others and that the loads may not be equal. If additional lighting load is to be added, more dimmers can be added. The dimmers need not be supplied from a single phase line, but can alternately be supplied by each phase of a three-phase system in order to balance the load on all three phases.

Control of all of the dimmers is from a single control station. The desired illumination level is fed to one dimmer which in turn transmits the information to the next dimmer. The transmission of this common desired illumination level is independent of the number of dimmers (within manufacturers limits) and whether the dimmers are supplied from one single phase feeder or from each of three-phase feeders.

3.2.6   Fluorescent Dimmer Control

The process of dimming fluorescent lamps is more complex than for incandescent lamps because the arc within the fluorescent lamp must first be established and then maintained throughout the dimming range. To establish the arc generally requires full voltage. To maintain the arc generally requires that filament voltage be maintained. When the voltage to the ballast is reduced, the filament voltage is also reduced unless a special dimming ballast is used. Dimming ballasts often are required for systems that use solid-state thyristor components to reduce voltage to the ballast. Where variable transformers provide dimming voltage, standard ballasts can generally be used.

The following manual fluorescent dimming systems are considered:

• Wall box dimmer

• Variable transformer dimmer

• Solid-state dimming system

POTENTIOMETER

ILLUMINATION LEVEL
INFORMATION FLOW

LOAD #1   LOAD #2

Φ N

LOAD #3   LOAD #4
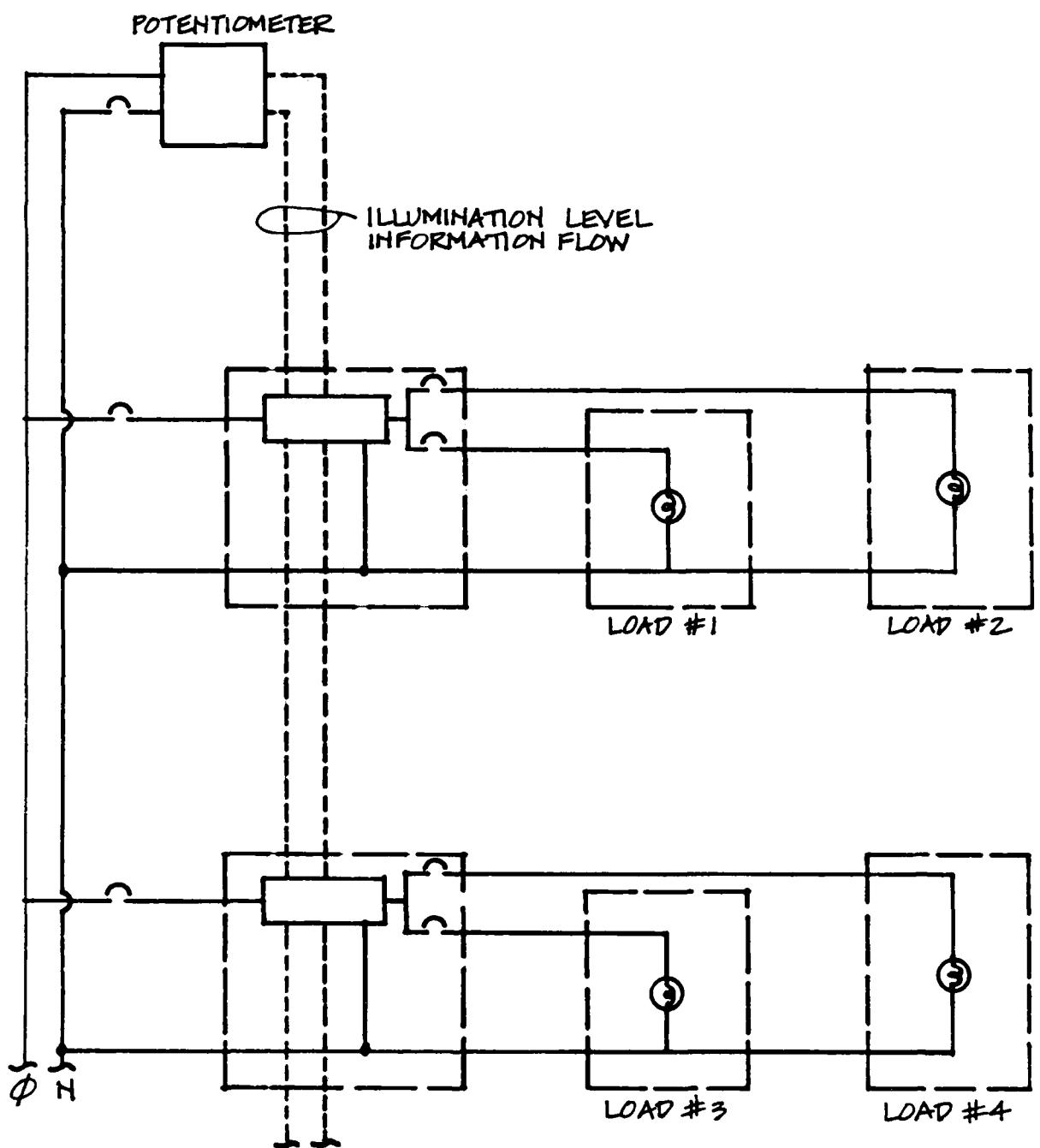
HIGH POWER INCADESCENT DIMMER CONTROL
FIGURE 3.13

A simple wall box dimmer for fluorescent dimming analagous to the low power incandescent dimmer is available, but requires that a particular dimming ballast be used. Although the need for a dimming ballast may not be deemed financially desirable, the fact that additional wiring is not needed in an existing installation can be a considerable incentive. For a new installation, the wiring requirements to the wall box are a minor consideration. The wiring of this two wire (single pole) device is similar to the manual control from one location shown in Figure 3-5. The ballast required for this installation is for operation of a single 40 watt lamp only.

Better control in a wall box dimmer is obtained by using the multiwire dimmers available from various manufacturers for use with a larger assortment of dimming ballasts and all lamp configurations than was permitted with the two wire dimmer. A dimmer compatible with a three-way switch is also available. The dimmer is always located closest (electrically) to the dimming ballasts and all other control stations are nondimming switching control stations. Some typical wiring diagrams (excluding the ballast to lamp connections) are shown in Figure 3-14.

Fluorescent dimming using standard ballasts (particularly applicable to an existing installation) is possible using variable transformers to reduce the voltage applied to the ballast. A system can be built of separately purchased components that include a variable auto-transformer and associated relay as shown in Figure 3-15. The system can also be an integrated package. A maximum of 40 percent voltage reduction is feasible with this type of system before the fluorescent lamp becomes unstable and the arc self extinguishes.

Also available for dimming standard fluorescent lamps are solid-state devices similar conceptually to the solid-state incandescent dimmers. These dimmers are available to operate with all types of fluorescent lamps and ballasts. The system is as shown in Figure 3-15, with the solid-state device in place of the autotransformer. Use of the disconnect relay is optional. This system, with standard, high output, or very high output lamps and standard ballasts, will dim from nominally 40 percent to 100 percent light output. However, one system available will dim energy saving 34-watt lamps and energy saving matched ballasts from 15 percent to 100 percent light output.

A commercially available system provides three phase control for 25 to 240 kVA of lighting with up to 40 percent voltage reduction. The variable transformers are motor driven and can be controlled remotely by manual or automatic control. The electrical energy wiring is shown in Figure 3-16. It should be noted that, in principle, this is a large

WALL BOX

DIMMER

ϕ

N

} TO BALLAST

A. 4-WIRE DIMMER

WALL BOX

DIMMER

ϕ

N

(NO NEUTRAL
CONNECTION)

} TO BALLAST

B. 3-WIRE DIMMER

WALL BOX
3-WAY SWITCH

WALL BOX
3-WAY DIMMER

DIMMER

ϕ

N

} TO BALLAST
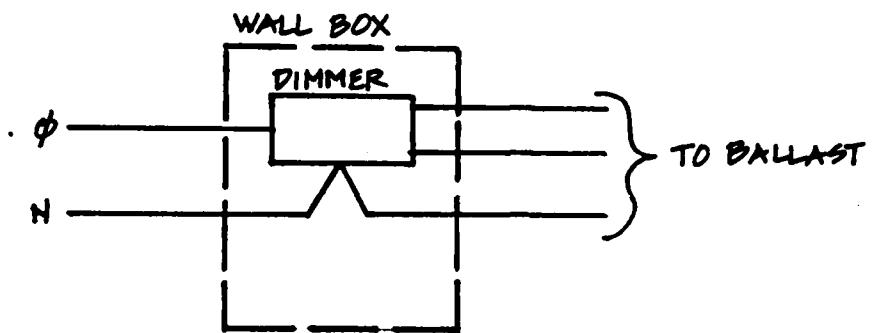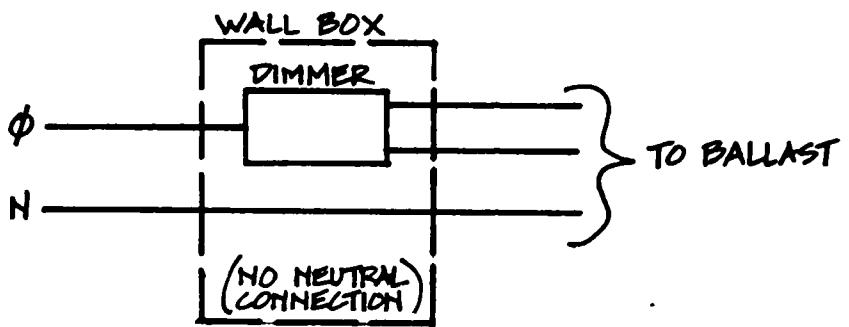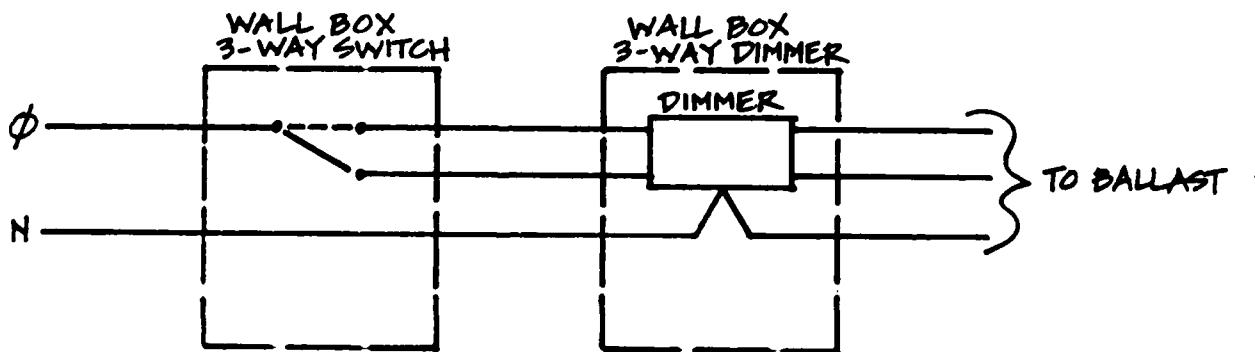
C. 3-WAY SWITCHING DIMMER

WALL BOX DIMMER CONNECTIONS
FIGURE 3.14
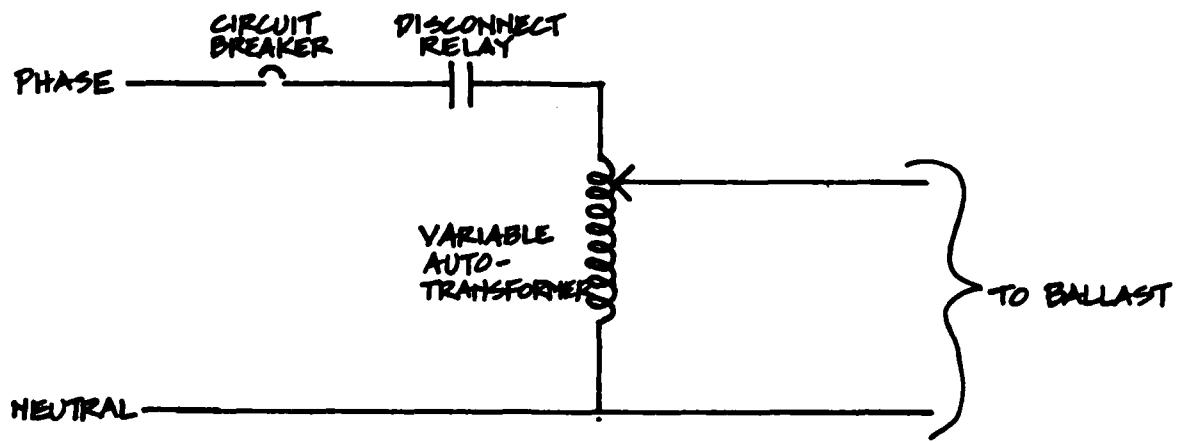
SIMPLE REDUCED VOLTAGE DIMMER
FIGURE 3.15
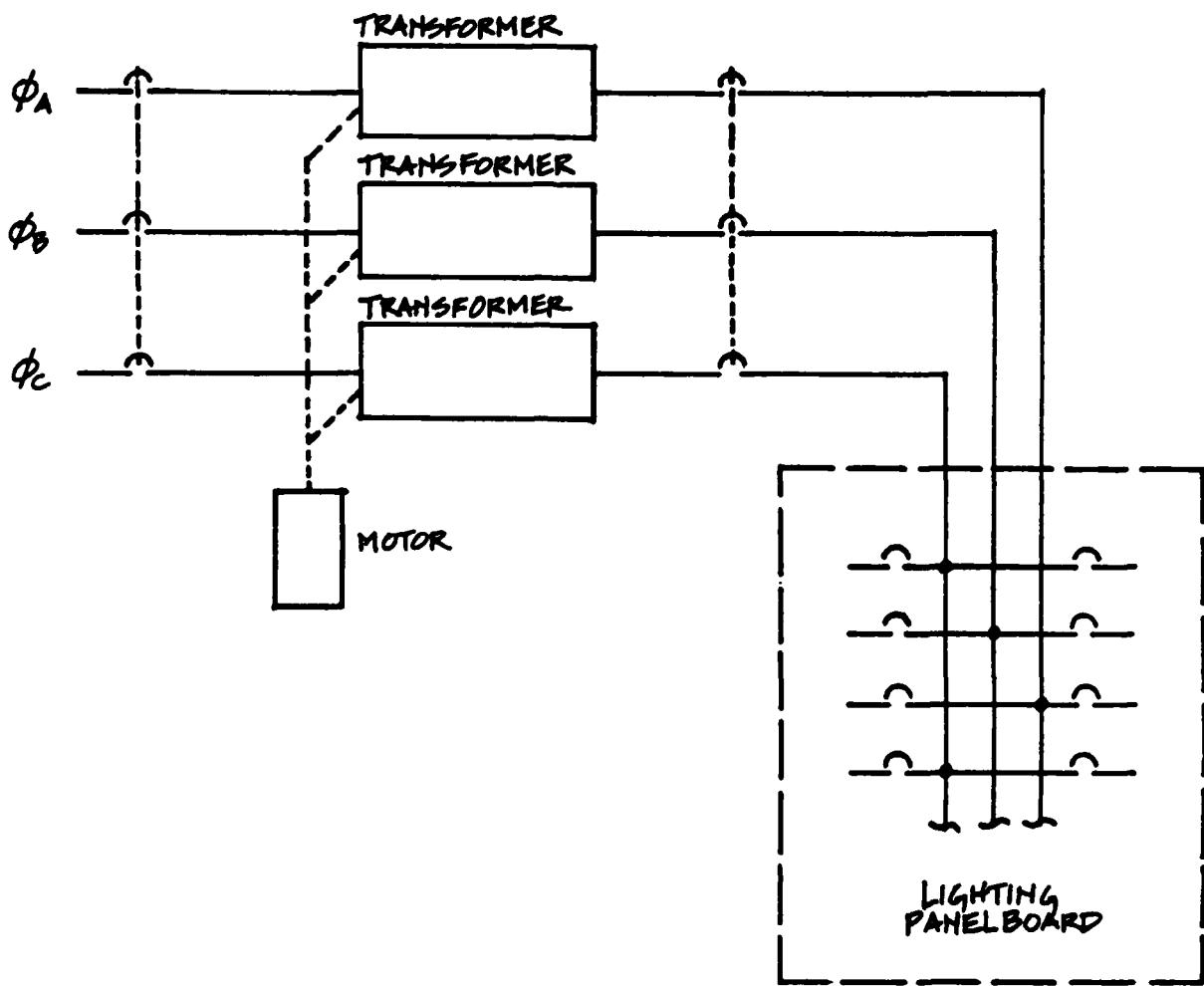
VARIABLE VOLTAGE CONTROL SYSTEM
FIGURE 3.16

system designed to control or dim a large lighting system, consisting of many luminaires as one control zone simultaneously. Reference should be made to the section on definition of control zones prior to considering the use of this type of dimming control.

Manual dimmer control of large numbers of fluorescent lamps is similar to the high power incandescent dimmer control system in Section 3.2.5. The control system is built of modules each of which can control typically from 40 to 80 fluorescent lamps. Each module receives electrical energy from a separate branch circuit and supplies energy to dimming ballasts. Two output circuit breakers are required for one circuit because two "hot" conductors from the dimmer and one neutral conductor are required for the dimming ballasts. One or more circuits may be provided from each module depending upon the specific load requirements. The desired illumination level is obtained from a potentiometer setting at a remote control station that provides control voltage to one module which in turn retransmits the control voltage to all other modules. A typical wiring diagram is shown in Figure 3-17. Except for the output conductors to the dimming ballasts, this diagram is similar to Figure 3-13 for High Power Incandescent Dimmer Control. Remote control can be similarly provided.

3.2.7   High Intensity Discharge Dimmer Control

High Intensity Discharge (HID) lighting can be dimmed by reducing the applied voltage after the discharge arc is established. Full voltage is normally required to establish the arc, but once established, the applied voltage can be reduced.

At the present time, there are no solid-state dimming systems for high pressure sodium (HPS) or metal halide (MH) lamps and only autotransformer type systems are used. When these lamps are dimmed, they tend to become unstable and produce significant color shifts due to abnormally low arc tube temperatures. The problems are associated with the lamps and not with the dimmer. Until new HID lamp technology becomes available, it is not recommended to try to dim these lamps.

Dimming of mercury vapor (MV) lamps using solid-state dimmers and standard ballasts is possible. The lamp arc must be established at full voltage and can then be dimmed to 5 percent output. Time delays measured in minutes occur in changing output lighting levels either up or down.

POTENTIOMETER OR SOLID
STATE VARIABLE
VOLTAGE SOURCE

DIMMER

DIMMER

TO DIMMING
BALLASTS

TO DIMMING
BALLASTS

TO DIMMING
BALLASTS

TO DIMMING
BALLASTS
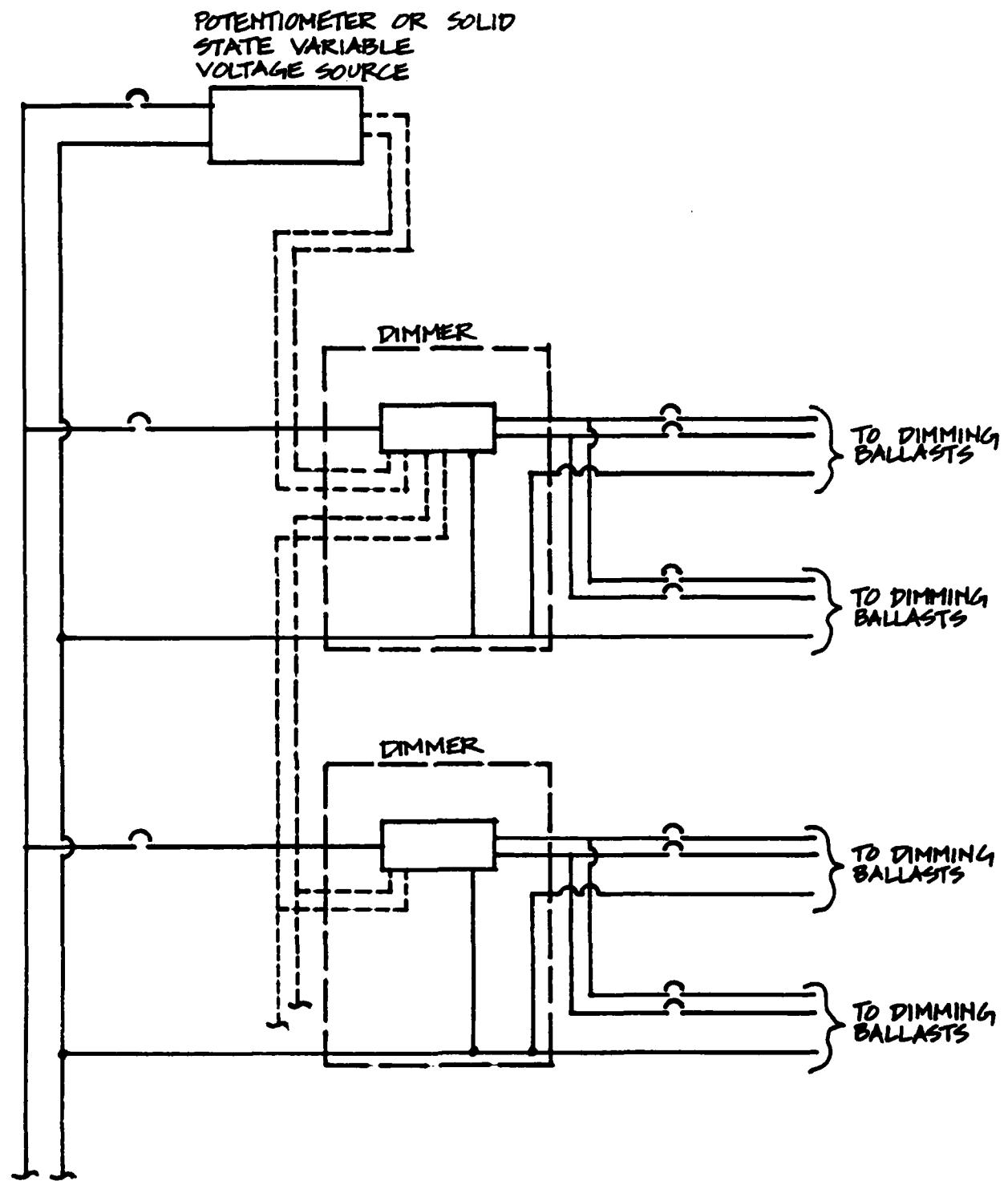
SOLID STATE FLUORESCENT DIMMING SYSTEM
FIGURE 3.17

3.3   OPEN LOOP AUTOMATIC CONTROL

3.3.1   General

There are very few control systems that can be both "open-loop" and "automatic". An automatic system operates without the intervention of a human being and an open-loop system executes predetermined changes at predetermined times and operates without directly sensing the need for illumination. There must, therefore, be some process which repeats and upon which a prediction can be made that there will either be a need for or no need for illumination. The process that repeats is "time" and two types of control systems are described.

3.3.2   Interval Timer

Consider a remote unattended pumping or radar station that is visited at irregular intervals for security and/or housekeeping reasons. During the visits, interior illumination may be required, however, if the lights are left on when the visits are concluded, considerable energy may be wasted. It may be predicted that a visit to the remote station will not last more than a given amount of time, therefore, a timer can be started when the lights are first turned ON to automatically turn the lights OFF after the given interval. This insures that energy is not wasted until the next visit. It is, of course, necessary to provide some means of overriding this control system in the event that, for example, maintenance or repair work for a substantially longer duration is required and lighting must remain ON.

Three basic types of interval timers are available--mechanical, electro-mechanical, and electronic operation and they are described in Section 2.2.3. The mechanical timer is electrically similar to a single pole switch and generally can replace a wall switch in the same wall box. Wiring of the mechanical timer is similar to Manual Control from One Location as shown in Figure 3-5.

An electro-mechanically operated timer consists of a clock motor drive, a clutch, and several sets of contacts. The control wiring diagram shown in Figure 3-18 provides for multiple control stations and resetting of the time interval during timing. The output contact can be specified to be either maintained or momentary. If maintained, the output contact can be wired to operate a luminaire or group of luminaires as in Manual Control from One Location, Figure 3-5, or to operate an electrically held contactor as in Figure 2-3a. If the output contact is a momentary type, then it can be wired as a control station as shown in Figure 3-8 for Low Voltage Control of Luminaires, or as shown in Figure 2-3b for Mechanically Held Contactor Control Circuit.
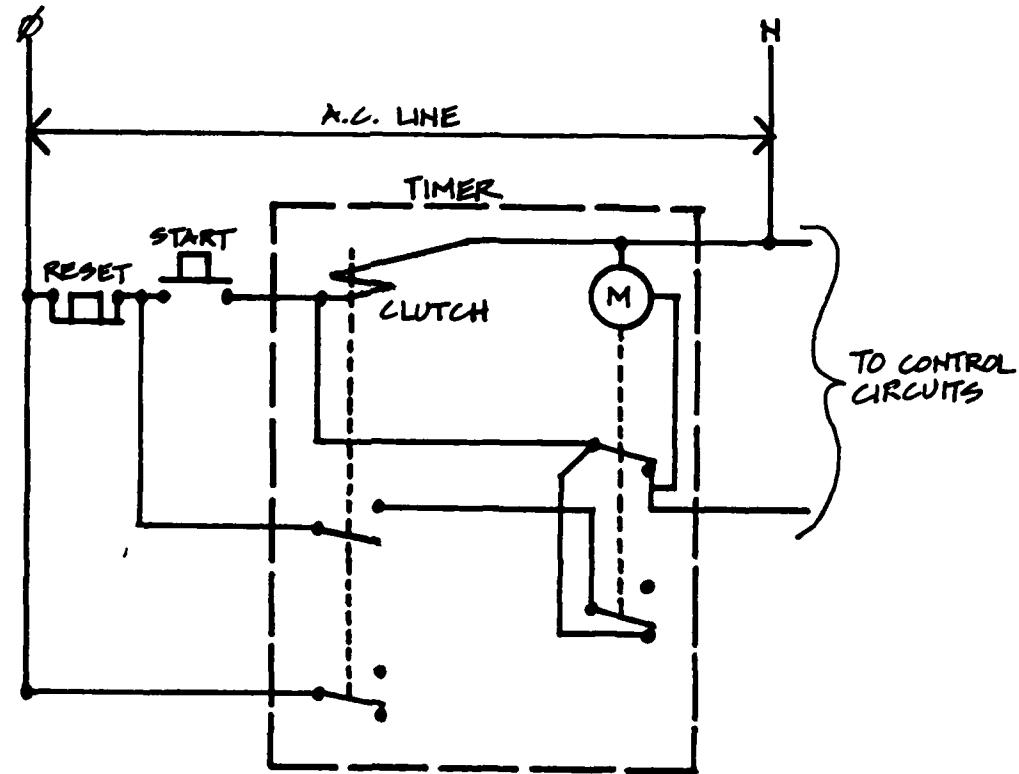
ELECTRICALLY OPERATED INTERVAL
TIMER WITH INTERVAL RESET
FIGURE 3.18

An electronic timer has all of the features of an electro-mechanical timer except that programming to provide for resetting the interval during timing and changing the timing interval is more easily accomplished electronically. The output contacts of an electronic timer may be limited to 120 volts and the ampacity may be low; however, when used in a low voltage or contactor control circuit or with an electro-mechanical relay, this limitation is not significant.

3.3.3 Time Clock

Consider an office space that is occupied on a regular basis, Monday through Friday, from 0800 to 1700, no one works on Saturday and Sunday and housekeeping is accomplished Monday through Friday from 2000 to 2200. It may, therefore, be reasonably predicted that general lighting is required Monday through Friday from 0730 to 1730 to account for the early arrivals and the late departures. In addition, a lower level of illumination may be predicted to be required from 1930 to 2230 each weekday. At all other times, only a small amount of night lighting for security is required. Because of possible exceptions, it would probably be necessary to provide overrides so that it is possible for individuals to work late or to work on weekends.

For the given conditions, it is assumed that the lighting system for each lighting control zone is divided into two systems--one for reduced lighting for housekeeping purposes, and both systems together for design illumination. Each of the systems may be individual luminaires, groups of luminaires, or groups of circuits of luminaires. Operation of each system of luminaires is assumed to be from either a single ON-OFF switch (direct operation or electrically held contactor), or from a set of momentary contact switches (low voltage switching or mechanically held contactor).

Two time clock functions are necessary to provide for the given conditions. One time clock "A" operates the housekeeping luminaries and would be programmed to go ON at 0730 and at 1930 during weekdays. The second time clock "B" for the remaining luminaires would be programmed to go ON only at 0730 on week days. Both time clocks would be programmed OFF at 1730. Time clock "B" would be programmed OFF at 1930, 2130, 2330 and perhaps an additional time after midnight to insure that luminaires turned ON locally are not left ON indefinitely. Time clock "A" would be programmed OFF at 2230 and perhaps an additional time after midnight. In addition, both timers would be programmed OFF at various times on Saturday and Sunday to insure that luminaires are not left ON.

The above system is particularly attractive when used with the low voltage relay system and the time clock operates a stepper master control. By providing a sufficient number of control zones, local control of lighting in limited areas

can be provided for those individuals working hours different than the given norm without providing lighting in unoccupied spaces.

A typical circuit is similar to Figure 3-10, Master Control Using Stepping Motor. Two of these circuits would be required, one for each lighting system. Each time clock would have momentary ON and OFF contacts. The ON contact would replace the manual momentary switch that starts the ON stepper motor and the OFF timer contact would replace the manual momentary switch that starts the OFF stepper motor. The remainder of the circuit is similar, limited only by the number of control zones and manual stations for each control zone.

3.4 CLOSED LOOP AUTOMATIC CONTROL

3.4.1 General

Closed-loop automatic control is obtained by providing a Sensor that determines the need for illumination or a change in the level of illumination. The Decision Element then determines if any change is required and provides an output to the Control Device. From the point of view of the control system, the Control Device and Controlled Elements are the electrical energy part of the system and are the same whether the system is Manual or Automatic.

The significant element of closed-loop automatic control is the source of the information and the logic which determines when to operate the Lighting System. For an illumination system that is either full ON or full OFF, either a maintained contact or a momentary contact can be utilized to operate a control zone whether it consists of a single luminaire or many circuits operated through relays or contactors. Similarly for a dimming system, the power wiring, whether it is for incandescent lamps or fluorescent or HID dimming ballasts, is the same whether the dimming control voltage comes from a manual control station or from an automatic controller. Circuits shown in this section are only for control since the power wiring is covered in the sections on Manual Control.

There are three classifications of Sensors for use in closed-loop automatic control that identify the need for more or less illumination. The first class is that of the presence sensor in any of the forms described in Section 2.2.4 which identifies the need for illumination without defining the quantity required. The second class is that of the photocell, whether the output is analog or ON-OFF, and in conjunction with the Decision Element defines the need for more or less illumination, regardless of whether the illumination will be utilized by anyone.

The third class is that of the electrical demand Sensor (not previously described) which is unrelated to the need for illumination, but is used for purely economic reasons. A description of the sensing and calculations required is beyond the scope of this Handbook but an application is described. If it is desired to reduce or limit demand, then illumination may be reduced automatically in response to the need for reduced electrical demand.

3.4.2 Presence Control

The basis of presence control is that if there is an individual present in a space, then there is a need for

illumination. Conversely, if the space is vacant, there is
no need for illumination. Thus, the control system, in
principle, is ON-OFF and any of the presence sensing elements
described in Section 2.2.4 could, in principle, be used.
Selection of the sensing medium, be it sonic, infra-red, or
microwave, is dependent upon the space use, physical size,
shape, contents and desired sensitivity. In general, these
sensors contain sufficient delay between ON and OFF (usually
none between OFF and ON except for threshold) so that the
lighting system will not be turned OFF immediately if the
individual(s) in the space do not move for a short period of
time.

The sensors generally have maintained output contacts
that provide a voltage output. The Sensor can, therefore, be
used to energize a Controlled Element directly if the load
current is compatible with the Sensor contact rating or the
contact rating can be increased by operating an intermediate
relay or contactor. See Figures 3-19a and 3-19b. Where it
is desired to have a momentary contact but only a maintained
contact is available, the circuit shown in Figure 3-20 can be
assembled with one time delay relay and one four pole relay
and connected as shown in Figure 3-19c. The adjustable time
delay relay allows for adjustment of the length of the
momentary contact closure.

The undercarpet mat operated by foot pressure does not
have the inherent time delay that the other sensors have. In
order to prevent intermittent operation of the lighting
system, a time delay relay should be used. A control circuit
showing the carpet switch and the relay is shown in Figure 3-
21.

3.4.3   Minimum Illumination - ON-OFF

Where daylight illumination must be supplemented at
night or during heavy cloud cover, a simple photocell may be
used to identify a minimum illumination below which
artificial lighting is necessary. Typical applications are
for parking lots, roadways, and building security.

The typical photocell combines the function of Sensor
and Decision Element because it can generally be adjusted to
turn ON at a given level of sky luminance (usually pointed at
the sky). The output of the Decision Element is a contact
closure providing control voltage to operate a luminaire
directly or to operate a relay or contactor. The output is
typically not a "dry" contact and the entire assembly oper-
ates at control voltage level of line voltage, typically 120
volts. A typical wiring diagram is shown in Figure 3-22 where
the control voltage is derived from a control transformer at
the contactor. Local Hand-Off-Auto (H-O-A) control at the
contactor is also shown.
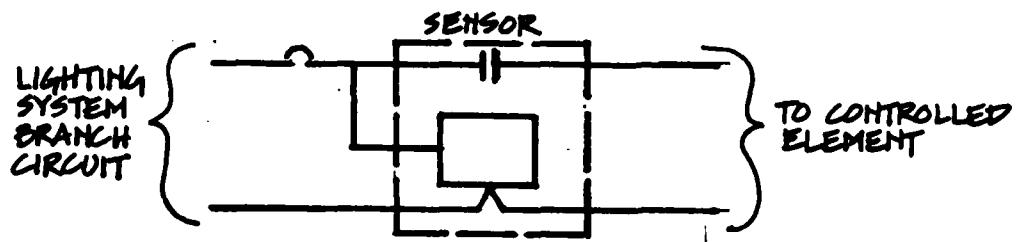
A. SENSOR OPERATING LIGHTING SYSTEM DIRECTLY
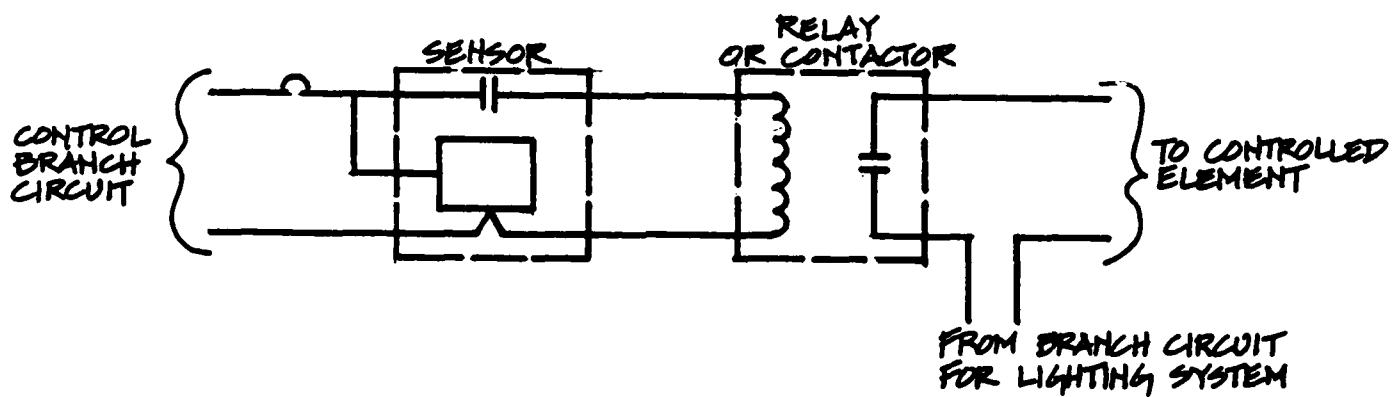
B. SENSOR OPERATING POWER RELAY OR CONTACTOR
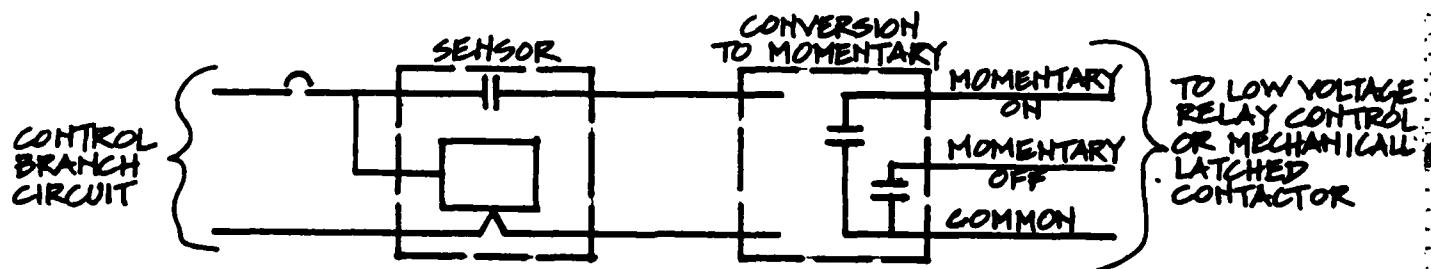
C. SENSOR MAINTAINED OUTPUT CONVERSION TO MOMENTARY CONTACT

SENSOR OUTPUT CIRCUITS
FIGURE 3.19

-80-

FROM
SENSOR
MAINTAINED
VOLTAGE

R1

CONTROL VOLTAGE

R1

R1

TD1

TD1

R1   MOMENTARY ON

R1   MOMENTARY OFF

COMMON
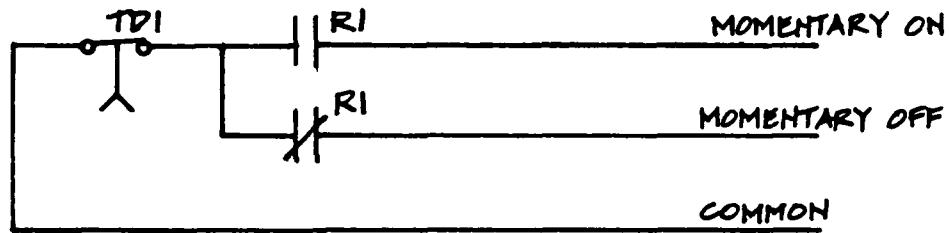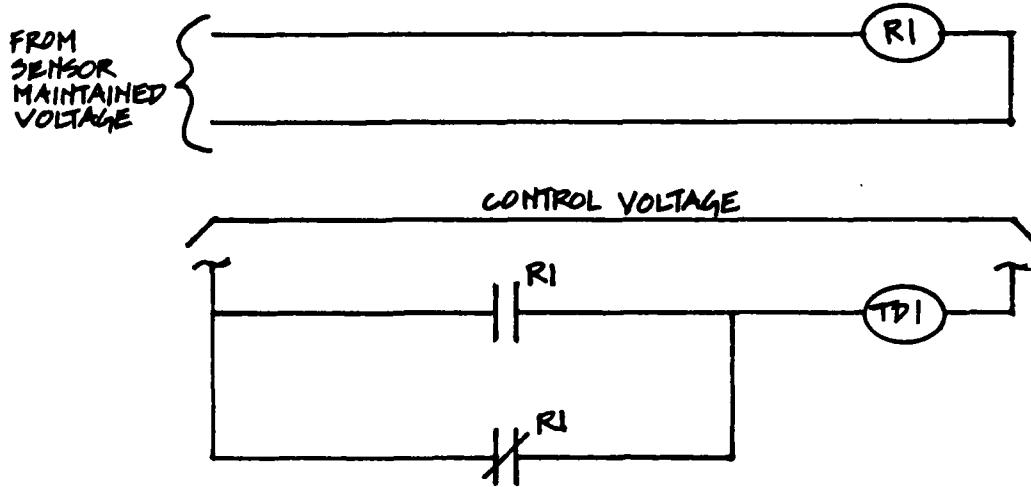
CONVERSION OF MAINTAINED CONTACT
TO MOMENTARY CONTACT
FIGURE 3.20
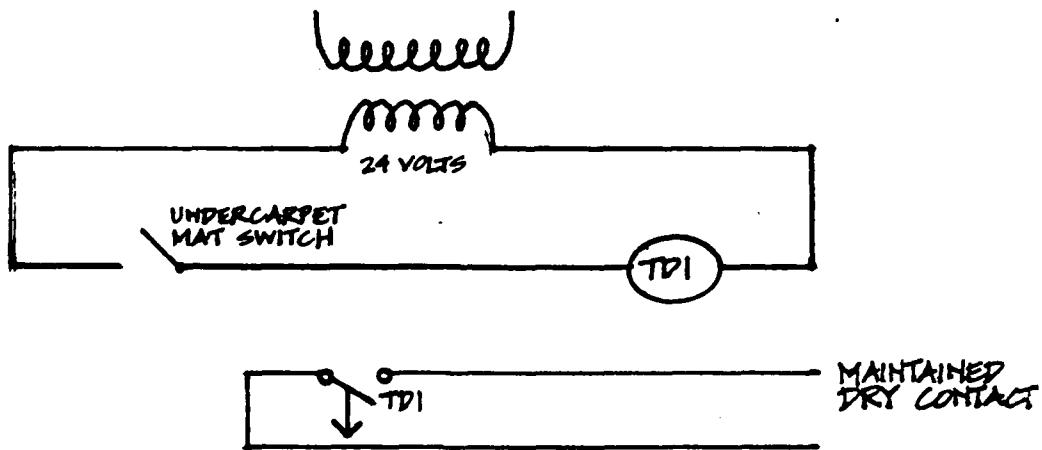
A. MAINTAINED OUTPUT

TD1 - DELAY ON RELEASE
TD2 - DELAY ON OPERATE
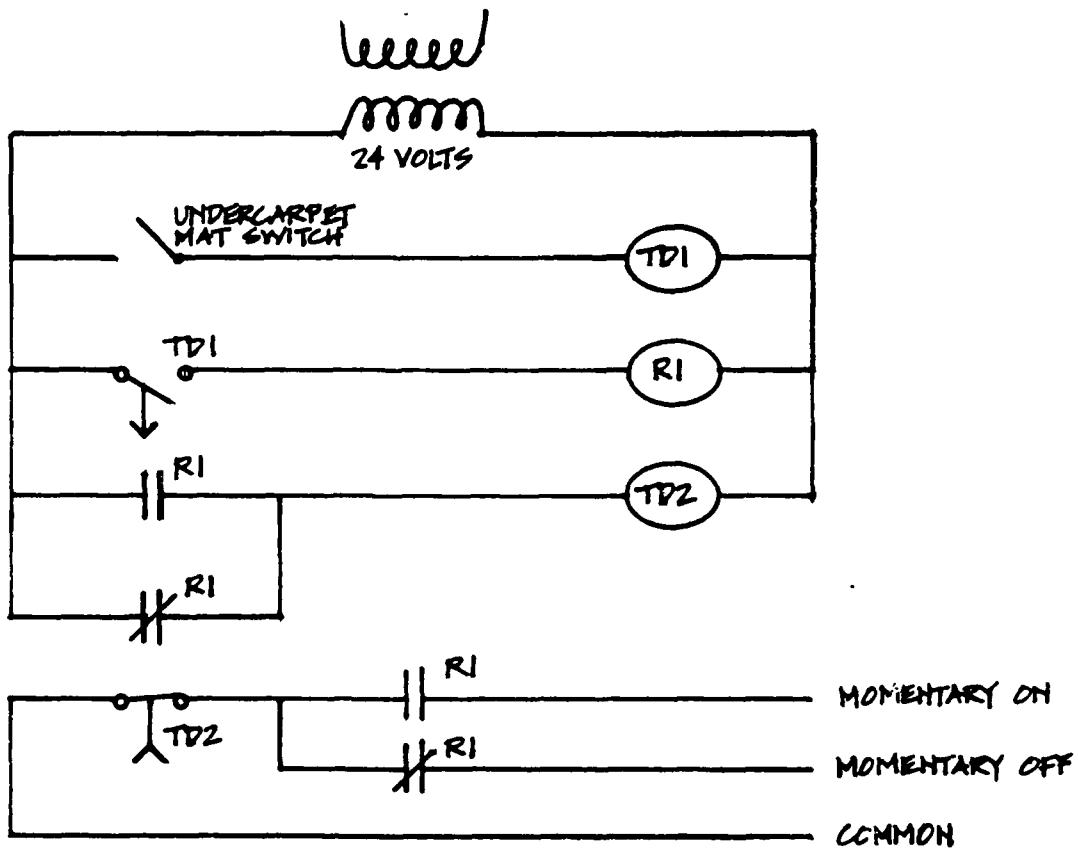
B. MOMENTARY OUTPUT CONTACT

UNDERCARPET MAT CONTROL
FIGURE 3.21

END

FILMED

DTIC

MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

THREE PHASE
POWER INPUT

CONTROL
TRANSF.

F   F

F 120V.

O
A   H

TO GROUP
OPERATED LOAD
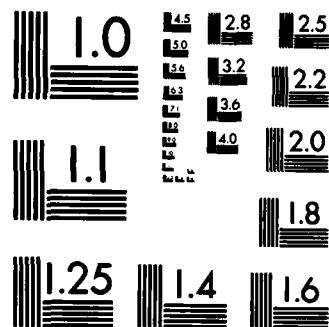
CONTACTOR
OPERATE COIL

PHOTOCELL   CONTACTOR
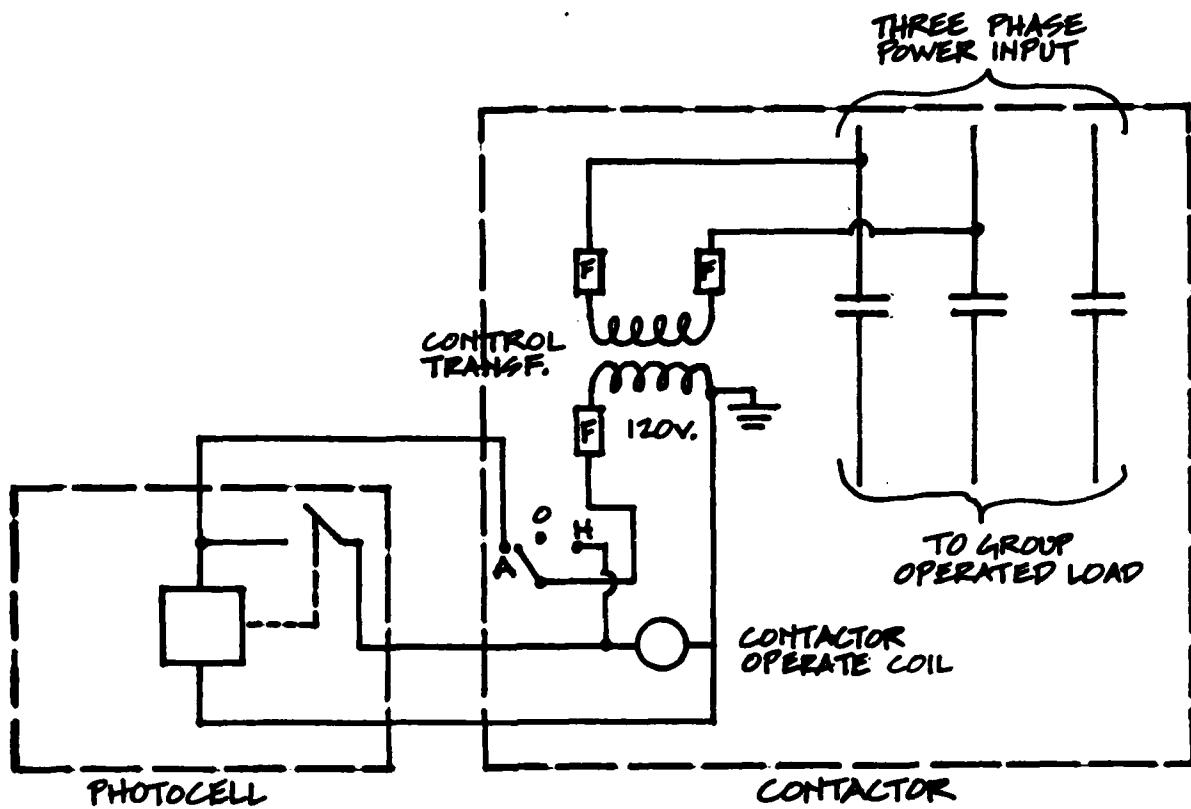
PHOTOCELL CONTROL OF CONTACTOR
FIGURE 3.22

CONTACTOR

PHOTOCELL   TIME CLOCK   CONTROL
                                       TRANSF.

M

CONTACTOR
OPERATE COIL
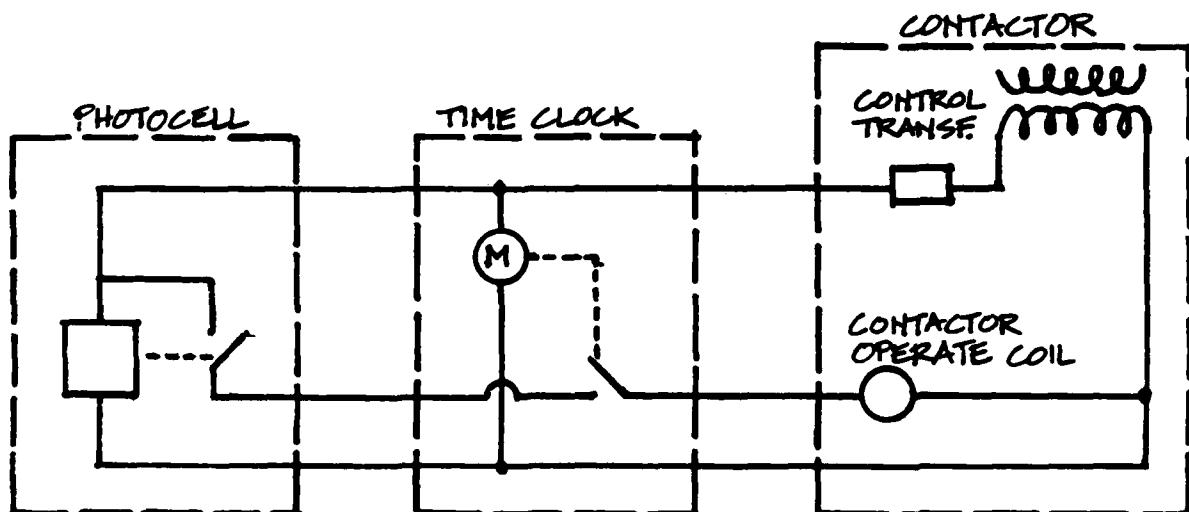
PHOTOCELL & TIME CLOCK CONTROL OF CONTACTOR
FIGURE 3.23

It is often desirable to limit the period that the luminaires are ON if the need for the illumination no longer exists. For example, a parking lot may be desired to be illuminated only until, say, midnight, after which it is known that there is no need for the illumination (security lighting should be considered separately). Addition of a time clock in the control circuit as shown in Figure 3-23 will permit the parking lot luminaires to be turned ON only after a certain time of day AND when the sky is "dark" and will turn the luminaires OFF at a given time, say midnight, even though the sky is still "dark". Although a time clock alone in this application may be sufficient, use of the photocell makes the system responsive to actual sky conditions through the seasons of the year and prevents luminaires from being turned ON when sky conditions do not warrant it.

3.4.4   Equi-illumination Control

There are two separate conditions, or combinations, where energy can be saved by maintaining a constant illumination regardless of changes that occur in the luminaire or in the space environment. First, in order to provide a minimum design illumination over the life of the luminaire, it is necessary to design for more than the minimum required illumination level due to recoverable and non-recoverable light loss factors such as lamp lumen depreciation with time and luminaire maintenance where accumulated dirt reduces the luminaire efficiency. Thus, initially and when lamps are replaced and/or the luminaire is cleaned, more illumination is provided and, therefore, more energy is used than needed. If the luminaire can be operated, initially, at reduced lumen output to achieve the minimum design illumination level requirement and then increase its output as lamp lumen depreciation and luminaire maintenance take their effect, energy will be saved over the life of the system. Second, if a given space, or portion of it, is illuminated by daylight for at least a portion of the time that lighting is required, energy can be saved by reducing the luminaire lumen output to a level where the minimum design requirements are achieved. With sufficient daylighting, the electric lighting, or a portion of it, may not be required. An equi-illumination system can take advantage of both of the above conditions simultaneously if the power circuits and control zone layouts are properly designed.

Fundamental to the design of an equi-illumination control system is a Sensor that responds to the illuminance reaching it, or, more correctly, the total amount of lumens reaching the sensitive element. The Sensor can only respond to illumination in a small very limited space and the system design must take into account how that space relates to the entire space being controlled.

A photocell sensor can be provided for each luminaire as shown in Figure 3-24a, or one photocell sensor can be provided for a group of luminaires as shown in Figure 3-24b. An individual sensor for each luminaire can be more responsive to lamp lumen depreciation, luminaire maintenance, and the local effects of daylight. The individual Sensor equipment will cost more than a single Sensor and installation will be more costly because each Sensor must be individually set in the ceiling and individually adjusted. An aesthetic disadvantage is that adjacent luminaires may not be uniformly illuminated, giving an appearance of a poor design even though the illumination at the working level rather than at the ceiling is relatively uniform.

The use of a single sensor for a group of luminaires is less costly from equipment, installation and adjustment points of view. However, there are disadvantages. All of the lamp lumen depreciation and luminaire maintenance factors are assumed to be the same. If the luminaire located at the Sensor has a characteristic different than the rest of the luminaires, the resultant light output and energy consumption over the life of the system will not be optimum. To minimize this tendency, it is advisable to locate the Sensor where it is under the influence of at least two and preferably four adjacent luminaires. In Figure 3-25 the Sensor is located equi-distant from pairs of fluorescent luminaires. If the luminaires are HID instead of fluorescent, the same considerations would be made with respect to the center of each luminaire (assuming they all have the same photometric distribution and are all directed vertically down). If the luminaires are not similar photometrically, or if the luminaires are not located symmetrically, then calculations should be made to determine the Sensor location that minimizes the influence of any one individual luminaires. When advantage is being taken of daylighting, care must be taken in locating a single sensor to avoid the effects of shadows, drapes, and window blinds.

3.4.5   Equi-visibility Control

Equi-visibility as a control concept is described here because the subject has been raised in the technical literature. In principle, illumination levels might be reduced since it is known that visibility is not necessarily a direct function of illumination. Therefore, instead of sensing levels of illumination, levels of visibility are sensed and, through the Decision Element, adjustments are made. If Equivalent Sphere Illumination (ESI) is used as the metric for visibility, often a reduction in illumination will improve visibility. At the present time there is no Sensor that can measure the visibility or the ESI at a given task location without being physically located at that task location. Thus, with today's technology, the concept is not practical.
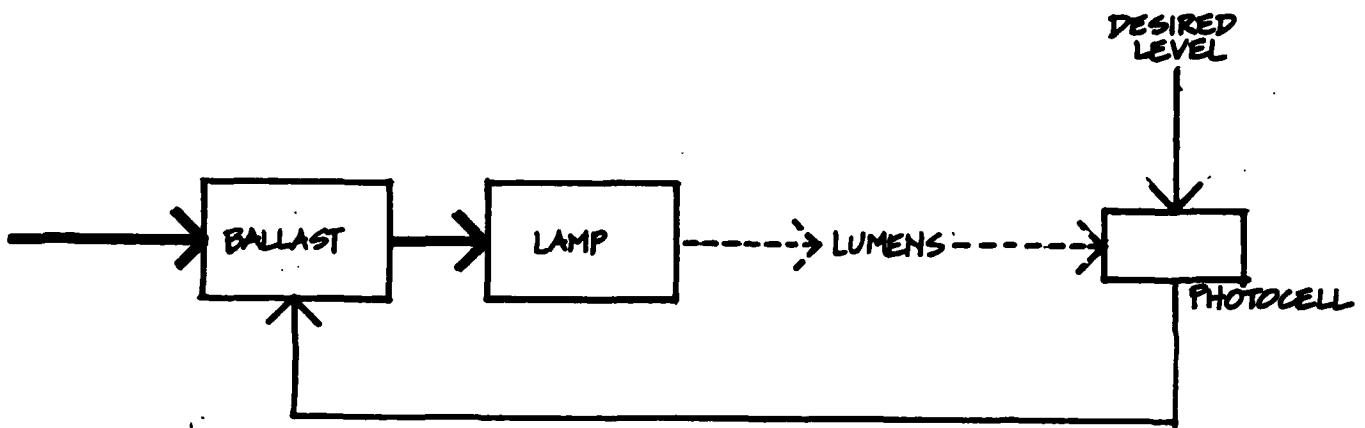
A. INDIVIDUAL CONTROL
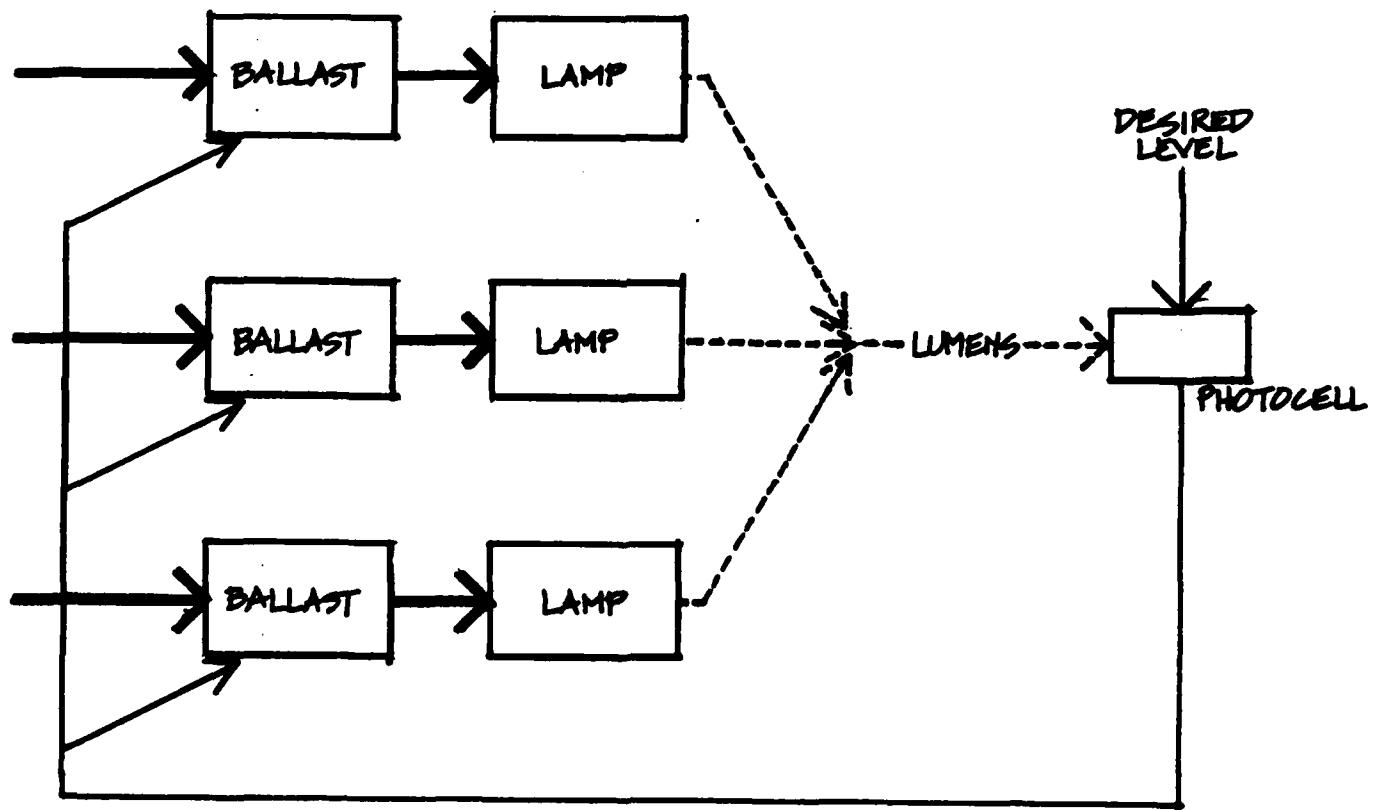
B. GROUP CONTROL

EQUI-ILLUMINATION CONTROL SYSTEM
FIGURE 3.24

SENSOR LOCATION

2'x4' FLUORESCENT (TYPICAL)

A. UNIFORM PATTERN

2'x4' FLUORESCENT (TYPICAL)
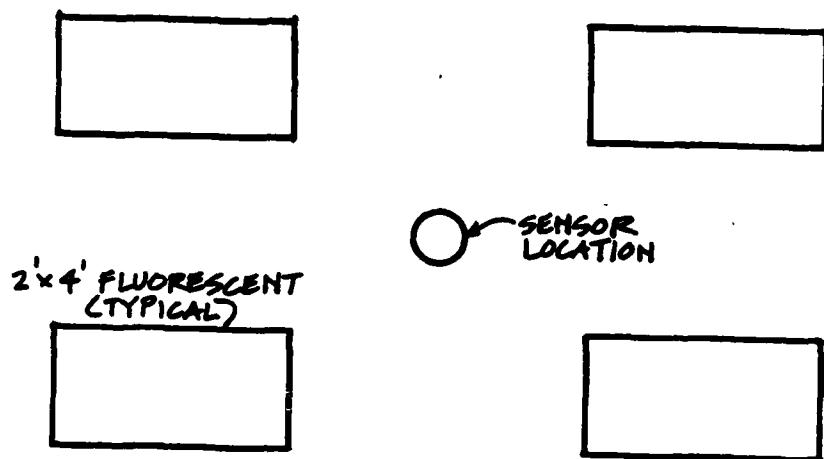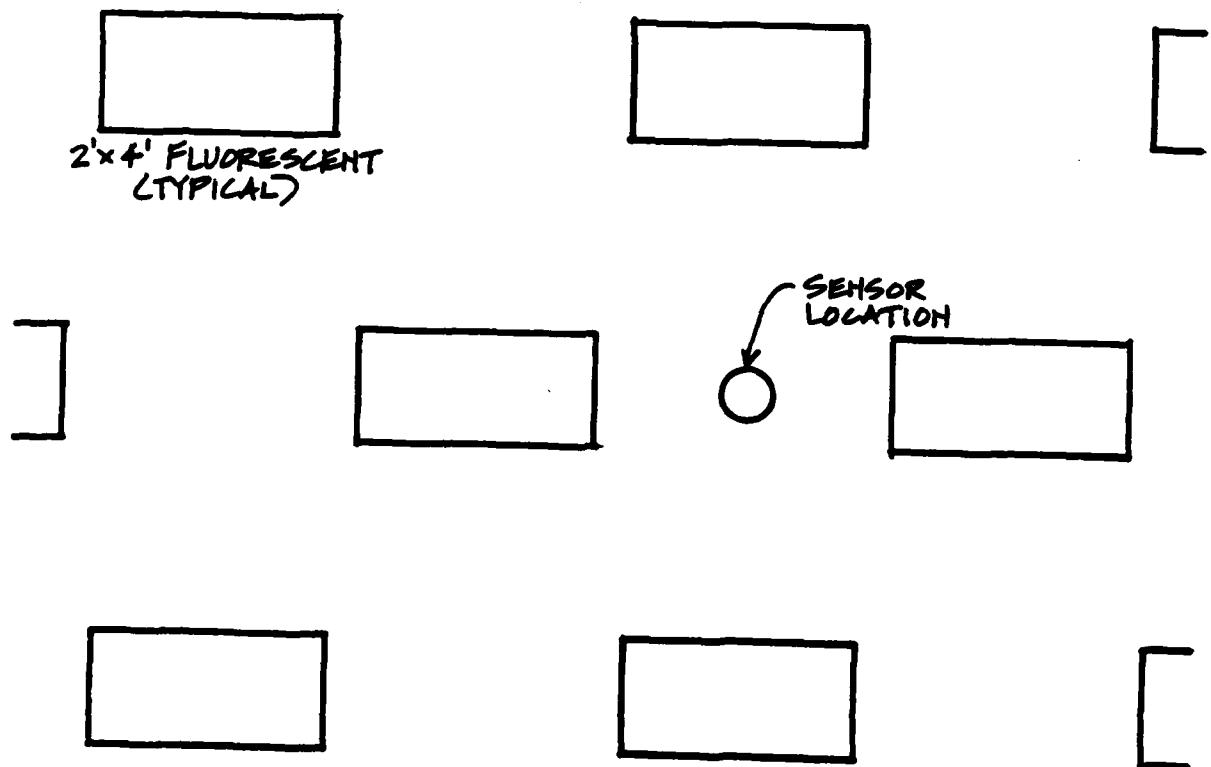
SENSOR LOCATION

B. CHECKERED PATTERN

SENSOR LOCATION TO MINIMIZE ABNORMAL LUMINAIRE INFLUENCE
FIGURE 3.25

It may be possible in the future that a remote visibility Sensor will be invented, or that for a given lighting system (both electric and daylight), the relationship between visibility at various locations and the illumination at various locations may be determined and programmed in a microprocessor for control of a lighting system. Until those technological breakthroughs occur, both from the standpoint of control hardware and the assessment of visibility, this control concept is not considered feasible.

3.4.6   Demand Limiting

Demand limiting is a procedure to reduce the cost of obtaining electricity from an electric utility company. When applied to lighting, it reduces both the demand charge and the energy charge. For a facility that generates its own electricity, demand limiting helps to prevent generator overload.

The process of limiting demand is most often limited to shutting down non-essential mechanical equipment whose non-operation for short periods of time does not affect any process or result in degraded working conditions. Shut down of a continuously running air handler in an office environment for 6 minutes out of a 30-minute period would probably not be noticed (except for the change in sound level), and will result in a reduction of both demand and consumption. Shut down of an electrically driven chiller would probably not be noticed since it would result in only a small increase in space temperature.

Lighting has typically not been used for demand limiting because its effect is so noticeable when turned ON or OFF and critical to a working environment. With the introduction of large dimming systems controlled from a central processor, a practical and acceptable means to limit demand is available. Illumination levels can be reduced by 10 to 20 percent, if done slowly, without the change being perceived. Continual operation at reduced levels may not be desirable.

A possible configuration for a dimming system with demand limiting is shown in Figure 3-26. Three separate lighting control zones are shown although more could be added. Each lighting system consists of a dimmer whose setpoint is driven remotely as described in Section 3.2.6 and shown in Figure 3-17. The control signal is an output of the central microprocessor (Decision Element) in place of the potentiometer. Each control zone has a photocell whose output is read by the central microprocessor (Decision Element).
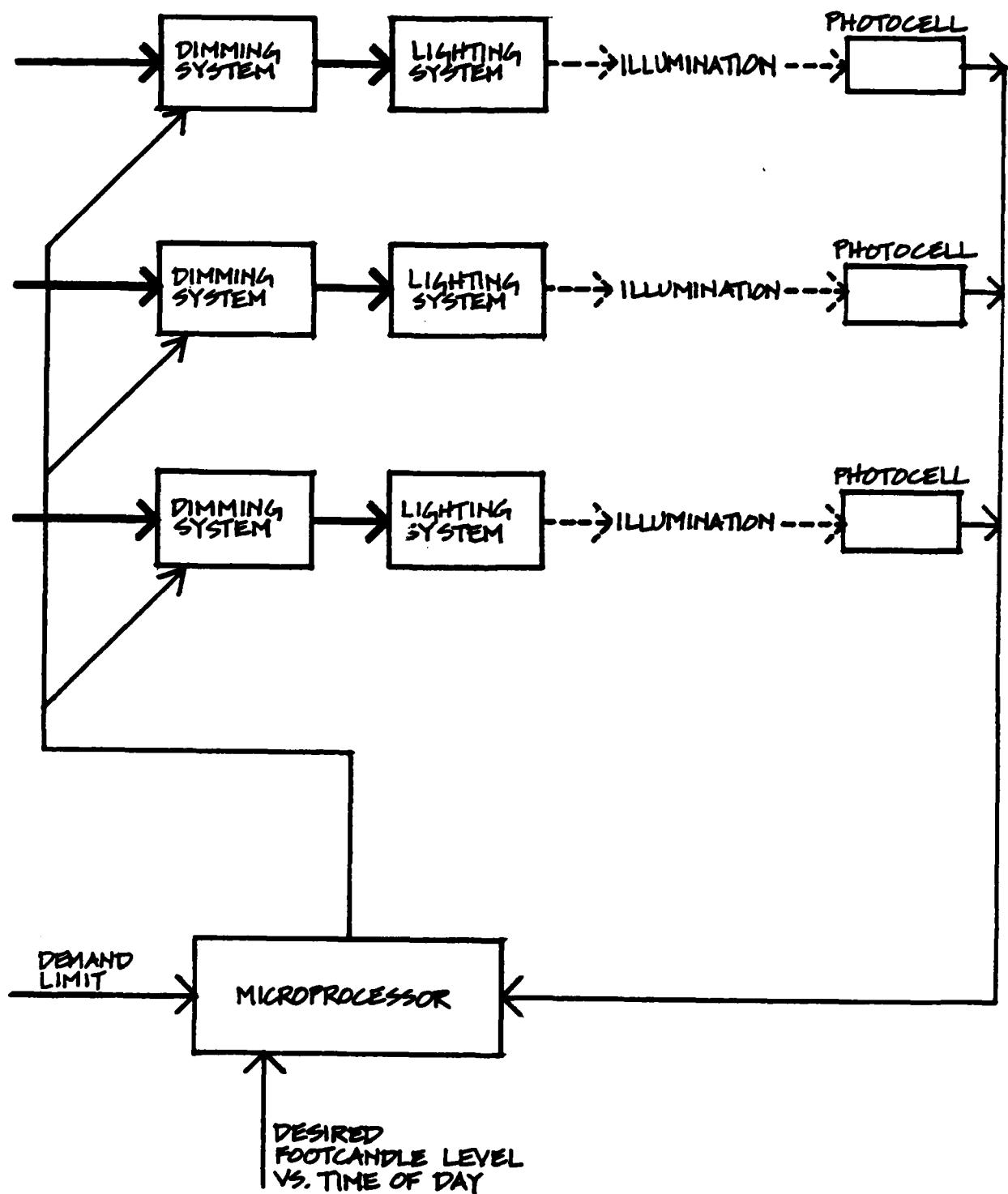
DIMMING SYSTEM WITH DEMAND LIMITING
FIGURE 3.26

A stored program input to the microprocessor is the desired footcandle level for each lighting control zone at each time of day. This will acount for early arrivals, lunch time, late departures, housekeeping, security, etc. The microprocessor compares the measured footcandle level for a control zone with the desired level for the given time of day and determines whether a given dimmer should be operated to raise or lower the illumination. This process is repeated for each control zone and then the whole cycle is repeated again and again.

If a "demand limit" signal is received by the micro-processor, the microprocessor can multiply each of the desired footcandle levels by a constant, say 0.8, and then use the new calculated values to compare with the photocell measured values. Thus, the overall lighting levels would be reduced to an 80 percent level automatically until the "demand limit" signal is removed.

Where lighting is a large proportion of the total electrical load, the use of remote dimming can be effective in limiting demand. For a building with 40 percent lighting load, a reduction of 10 percent of the lighting load for short periods of time can reduce the electrical utility charge by up to 2 percent (based on demand charges accounting for approximately one-half of the utility bill).

4. APPLICATION

4. APPLICATION

4.1 SELECTION CRITERIA

4.1.1 Purpose

Ideally the design of a lighting system and the design of the control system to regulate the lighting system should occur simultaneously in order to be able to optimize both systems with respect to cost and performance. Often, this ideal is not achieved and a lighting system is designed and circuited without regard to how it will be controlled. The lighting system may be designed to meet the maximum illumination requirements of the space. "Maximum" means maximum electrical demand and energy consumption. "Maximum" may also mean an illumination level that is not suited for the performance of at least one of the visual tasks in the control zone. For example, lighting intended for a card reading task may produce glare and severely limit the ability to read information on a video (CRT) screen. Maximum illumination "requirements" implies that this condition should occur throughout the life of the lighting system regardless of Lamp Lumen Depreciation, Luminaire Dirt Depreciation, and other Light Loss Factors.

The purpose then of a lighting control system is one or both of the following:

- To provide the illumination necessary and desired to perform the specified visual task or tasks in the given space; and

- To minimize the cost of operation and/or conserve fuel and energy.

Many of the techniques and circuits given in this Handbook are applicable to both purposes above. There is, however, no necessity for economic justification of a control system to provide required lighting except with respect to alternative systems that provide the same lighting performance. With respect to controls for minimizing system operating costs, it is necessary to show that the necessary capital investment (you rarely get something for nothing) will provide a "reasonable" return on that investment.

This Handbook is directed towards the design of lighting controls to minimize the cost of operation and the means to evaluate the expected savings.

4.1.2 Visual Task

An understanding of the visual tasks to be performed is fundamental to the design of a lighting control system. Not only is it necessary to know what the tasks are, but knowing when and where the tasks will be performed is required to efficiently select control zones.   Often multiple visual tasks of differing illumination needs are performed in close proximity to each other.   A decision of whether to have a single control zone or multiple zones covering each of the tasks is required.

Where multiple tasks are performed at different times in the same space, the need for different lighting levels is indicated.   There are various ways to obtain the different levels but a knowledge of the increments or steps between each of the task requirements will influence the selection of a particular method. As an example, if there are two tasks, one requiring twice the illumination of the second, a simple control system of switching OFF half of the lights might suffice. If, on the other hand, there are four or five tasks whose visual requirements range from full ON to 10 percent of maximum, a dimming system might be the most eonomical way to provide the right amount of light when and where it is needed.

Selection of lighting levels for each visual task is a multi-step process that requires an identification of the type of task, the seeing capability of the worker as influenced by age, and the speed and accuracy requirements for performance of the task. Each of these factors influences the selection of a required illumination level. These factors may change with time in any given space. Thus, it is desirable to identify the probability of changing illumination requirements and plan a control system that is easily adaptable to those changing conditions. Where changing requirements are anticipated to be incrementally large, then a switching system may be desirable.   Where the changing increment requirements are anticipated to be small, such as due to aging of the worker, a dimming system may be able to accommodate the changes with a mere setpoint change on a potentiometer. Selection of illumination requirements are beyond the scope of this Handbook and reference should be made to the IES (Illuminting Engineering Society of North America) Lighting Handbook,   latest   edition,   Recommended   Procedure   for Selecting Illuminances.

4.1.3 Occupancy

The nature of the occupancy of the space in terms of frequency and duration is important in the selection of a control   system   to   conserve   energy.   Except   for   certain special   considerations,   typically   building   security   and plant growth in atriums, if the space is not occupied, there

is no need for illumination if the intent is to minimize the cost of utilizing electricity. Various combinations of use frequency and duration of occupancy can occur. The frequency can be from less than one time per day to more than several times each day. The duration can range from several minutes each time, to continuous use. Considering the combinations, some general guidelines follow but it should be emphasized that each application is unique and all approaches to control should be considered:

- Equi-illumination systems should be used mainly where the total occupancy time averages 6 to 8 hours per day or more. Otherwise, the cost of the control system will probably be excessive in relation to the energy costs saved.

- Presence Sensors may be used in spaces that are occupied less than once each day or for spaces that are only used for short periods at a time.

- Timers may be used in place of Presence Sensors in spaces that are only occupied for short periods at a time and where there is no hazard or inconvenience if lights are turned OFF while the space is still occupied.

- Time clocks may be used for spaces that are occupied once a day or less and generally at the same time of day for a definite period of time.

4.1.4   Daylight Availability

The availability of daylight is not sufficient to warrant its use in a control system to conserve energy. Daylight must be available in the quantity and quality to make it economically viable. First of all, it must be available in sufficient quantity and during the hours that the space is in use. Second, it must be available in equal quantity over a space large enough to be controlled together. Larger spaces with equal daylighting will result in fewer lighting control zones.

Calculation of the useful availability of daylight can be done by hand calculations or by computer simulation. Various technical papers have described procedures, but they are beyond the scope of this Handbook. It is assumed that the designer has obtained the data by some means. It should be noted that, particularly for a retrofit application, measurement of daylight in an existing space is a valid means of determining daylight availability.

4.1.5   Load Shedding

Lighting is rarely used for load shedding purposes because, in general, lighting that is ON is required for performing necessary tasks and if turned OFF, would render the space unuseable. With the advent of dimming systems, there is a potential for load shedding. The human eye is very adaptable to varying lighting conditions without signalling to the brain immediately that the available illumination is more or less than that which is necessary. In fact, the illumination can be reduced to a level that could result in reduced productivity if used for extended periods of time, yet the eyes would adapt and no detrimental effects would occur if the reduction occurred slowly and only for a short period of time. If illumination levels are reduced in half instantaneously, the event is noticeable. If the change occurs over several minutes, the initial and final illumination values would determine if the change is noticeable. In general, reductions in illumintion level of 10 to 30 percent that occur over several minutes and that do not last for more than several minutes will probably not be observed.

In order to evaluate the application of dimming to load shedding, it is necessary to understand the applicable rate structure and how billing demand is determined. See Section 2.6. As an example of limiting building demand by shedding lighting load, consider a building having a 100 kW dimmable lighting load, a maximum mechanical load of 110 kW, a utility demand period of 30 minutes and a desire to limit the demand to 200 kW. If the mechanical load is 110 kW throughout the demand period and cannot be reduced then at the end of the demand period without load shedding there would be an energy usage of 105 kilowatt-hours (210 kW x 0.5 hr.). This energy usage represents an average demand of 210 kW and is 5 percent above the desired value. It is desired that the energy usage in the 30-minute demand period will not exceed 100 kWH representing 200 kW of average demand (200 kW x 0.5 = 100 kWH).

In order to limit total billing demand to 200 kW and, therefore, 100 kWH for the 30 minute demand measuring period with a fixed mechanical load of 110 kW, the lighting load must not average more than 90 kW during the same measuring period. The lighting could be dimmed to 90 percent power input, and thereby, demand only 90 kW during the 30 minute period. The total energy used would be 110 kW x 0.5 hr. + 90 kW x 0.5 hr. or 100 kWH as desired.

An alternative strategy would be to operate the lighting system at maximum output for a fractional part of the demand period, and then dim the lighting sufficiently so that the total energy used would be 100 kWH. The example shown in

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Figure 4-1 depicts full lighting load of 100 kW and the mechanical load of 110 kW for the first 20 minutes of the demand period. At that time a total of 70 kWH have been used in the period (210 kW x 1/3 hr.). Lighting is then dimmed to 70 percent for the remaining 10 minutes. The energy used in the last 10 minute period is 30 kWH (180 kW x 1/6 hr.). The total energy used during the demand period is 100 kWH, giving an average power demand of 200 kW.

The mechanism by which demand is measured and the decision of when to shed load, which load to shed, and how much to shed is part of a Demand Limiting Controller. Further discussion is beyond the scope of this Handbook. It is important to recognize that dimming a lighting system is a feasible means of shedding load if the total dimmable load is a significant part of the total demand load.

It may not appear that limiting of demand by 5 percent is significant. A one time exceeding of previous peak demand by 5 percent for a facility with an 1,000 kW demand could result in a total additional billing cost of $1,000 - $2,000 depending upon the specific rates and ratchet clauses.

4.1.6   Budget Limitations

Budget limitations have a very strong influence on the selection of lighting control systems. Where construction or first costs are limited and additional funds are not available regardless of the life-cycle cost or return on investment, design of the initial installation should be planned for ease in adding a control system at a later date. The circuiting and physical placement of equipment and extra pull boxes can make the difference between high and low cost conversion to a more sophisticated control. Planning can also make a significant difference in the amount of system down-time or overtime requirement for a later conversion.

The lowest first cost control system utilizes circuit breaker panelboard manual switching. If branch circuits are loaded to maximum capacity, then one 20 ampere, three phase, four wire circuit at 480Y/277 volts can control approximately 6,000 square feet at a design value of 2 watts per square foot. At 208Y/120 volts, the space that can be controlled by one three phase circuit is approximately 2,500 square feet at the above design value.

In order to provide for future addition of local switches, contactors, low voltage relays, and/or sensor control, the following low cost principles should be considered for initial construction:

- Provide a neutral conductor for each single phase circuit. Do not use three phase, four wire circuits as they are difficult to separate.
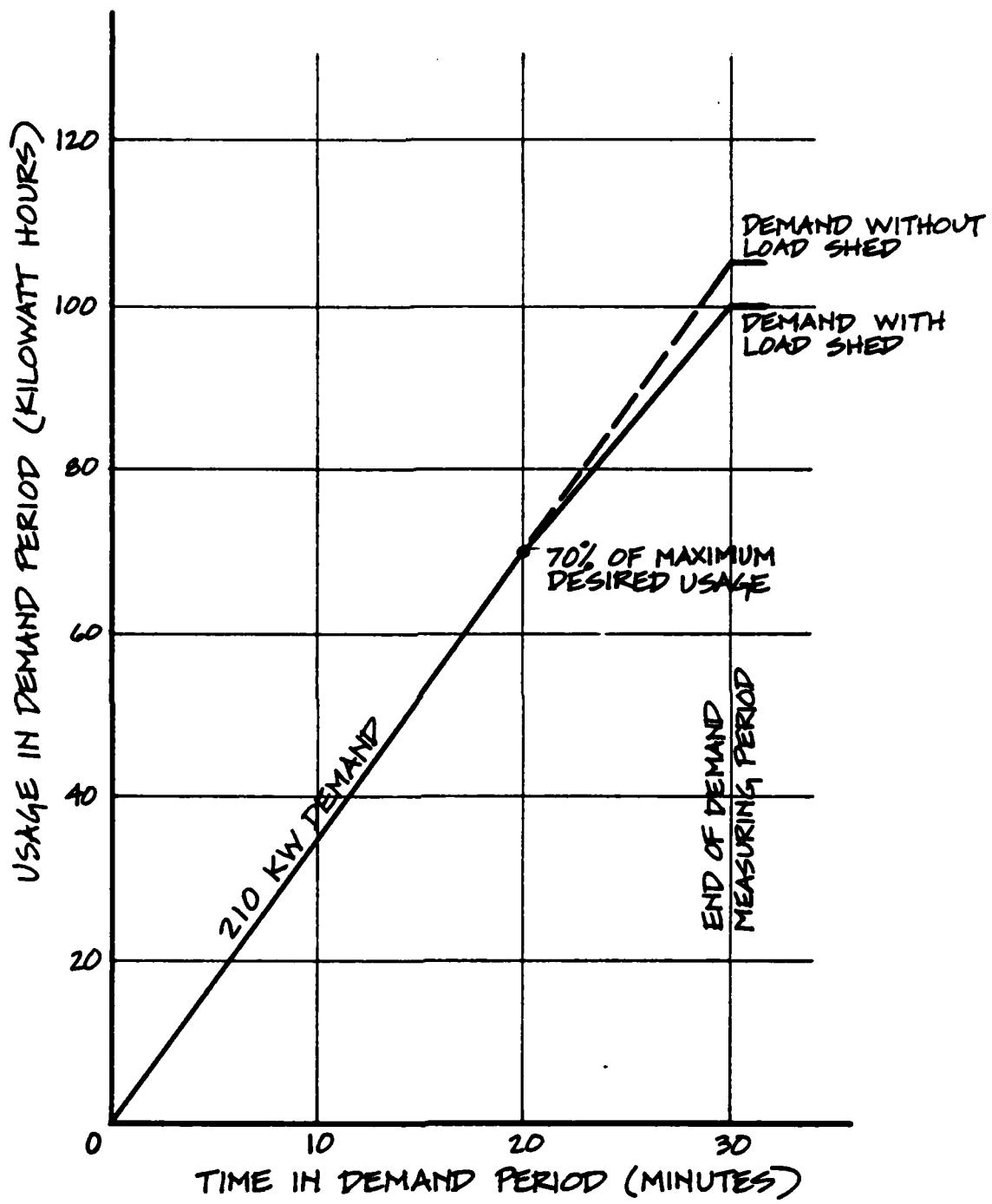
LOAD SHEDDING EXAMPLE
FIGURE 4.1

Axis labels and annotations:
- USAGE IN DEMAND PERIOD (KILOWATT HOURS)
- TIME IN DEMAND PERIOD (MINUTES)
- DEMAND WITHOUT LOAD SHED
- DEMAND WITH LOAD SHED
- 70% OF MAXIMUM DESIRED USAGE
- END OF DEMAND MEASURING PERIOD
- 210 KW DEMAND

- Unless a manufactured wiring system (plug in) or track is used for luminaire power connections, all taps to individual luminaires should be made at junction boxes separate from the luminaire and accessible without removing the luminaire.

- Provide "home runs" to panelboards for the smallest space that could be considered a lighting control zone even if several of these spaces are combined initially into one branch circuit.

- Provide junction or pull boxes at or near locations anticipated for future local switches, dimmers, and/or relays. The cost of the additional boxes is negligible particularly if splices are not made in them.

- Where it is anticipated that contactors, dimmers, and/or relays will be installed in the future at a panelboard, do not install line or load conduit directly into the panelboard without a 90 degree bend or some form of pull box. Removal of conduit and wiring after installation to make room for future equipment is typically very difficult and costly. Figure 4-2 shows one of many possible installation procedures to anticipate future requirements.

Budget limitations during initial construction or a major remodeling can often make future energy conservation by lighting control not economically attractive even though the payback, if installed initially, was desirable. The additional costs that arise due to the need to remove ceilings, rewire luminaires, install conduits in finished walls, etc. can be minimized with adequate attention to construction details as described above.

4.1.7   Retrofit Applications

All of the control methods, whether manual or automatic, as described in Chapter 3, are available when a control system design is integrated with the lighting system design. This, of course, is the most desirable approach from an energy conservation point of view. When a control system is added on to an existing lighting system, some of the control methods may not be economically desirable, while others may be particularly easy to add on. The choice will often be a compromise between the available energy to be conserved and the specific way in which the lighting system has been installed.

Certain components and systems are particularly useful for add-on applications because of the ease in which the components can be mounted and/or wired into an existing system. The following items should be particularly noted:

A. TYPICAL

B. DESIGN FOR FUTURE ADDITION OF CONTROL RELAY/CONTACTOR
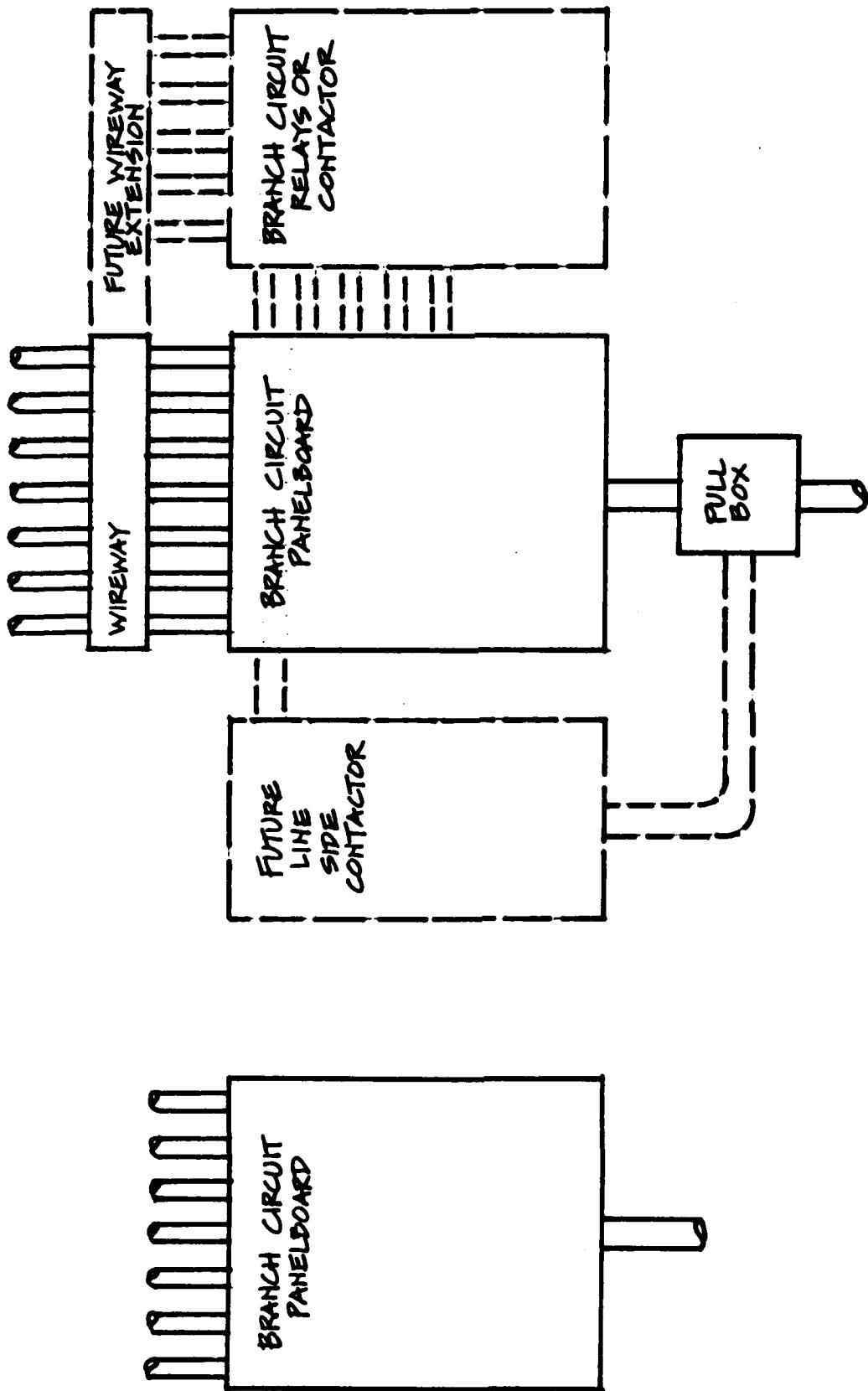
CONDUIT RISER FOR BRANCH CIRCUIT PANELBOARD
FIGURE 4.2

- A manual timer is typically designed to replace a manually operated toggle switch. No additional wiring or hardware is required.

- Manual dimmers for incandescent replacement of manually operated toggle switches require no additional wiring.

- Remote dimmers for fluorescent lamps with standard ballasts permit the lighting level of an existing space to be manually reduced. The dimmer is typically located at a branch circuit panelboard and a screwdriver adjustment sets the output level of all lamps on the dimmer. This system can be easily converted to an equi-illumination system by the addition of a photocell. The wiring to the photocell located in the ceiling does not require conduit, even in a plenum space, if wire listed for the application is used.

- Carrier controlled relay systems are designed to utilize the existing wiring system as control conductors. The relays of at least one system are direct replacements for manually operated toggle switches and retain the local control capability. Neutral conductors must be available. Remote operation, either manual or automatic, can be added wherever it is convenient to make a connection into the wiring system, typically at the branch circuit panelboard.

- Low voltage relays permit local manual control stations to be added without the necessity of using conduit even in a plenum (air return) ceiling or finished wall provided that the wiring is listed for the application. Teflon coated (low flame point) multi-conductor cable is available and the relays may be mounted in the luminaire, in the ceiling space (accessible), or at the branch circuit panelboard.

4.1.8   System Design versus Design from Components

The design of simple control systems is typically very straightforward. The designer first understands and recognizes the need for a control system. The designer is aware of the capabilities of various control components either from this Handbook, manufacturers' brochures, or from his previous experience. He can then pick and choose components that can be wired together and will satisfy the system requirements.

As systems become more complex, from manual to open loop automatic to closed loop automatic, the capabilities of the

equipment becomes greater. It becomes exceedingly difficult to pick and choose components for complex systems and be assured that they will perform together as a system as required. In addition, it has been found that manufacturers of electronic equipment can often add or delete features to their standard equipment at little or no additional cost. It, therefore, may be advantageous to write performance specifications for complex control systems and let the manufacturer determine the proper combination of components. Manufacturers of systems are able to design a system to specifications that often will be less costly than purchasing standard components with unnecessary or undesired features. The performance specification is simply a description of how the system is to perform under all operating conditions, and is information that a designer should know prior to designing any control system, whether it is simple or complex.

4.2   SENSOR LOCATION

4.2.1   Photocell

Photocells need to be located where they will not be influenced by light other than that which it is intended to sense. For outdoor applications where it is desired to sense the availability of light from the sky, the photocell is generally directed toward the Northern sky to prevent direct sunlight from overdriving the photocell. Care must be taken in specifying the photocell to insure that it can be used in the desired environment.

For indoor applications where the photocell is used to sense the illumination at a particular location for equi-illumination systems, conditions necessary to consider are:

- That the given sensed location is representative of the space to be controlled;

- That the photocell is not unduly influenced by the performance of a particular luminaire;

- That the photocell is not sensitive to extraneous light sources; and

- That the reflectivity of the area being sensed cannot be easily changed such as by inadvertent scattering of high gloss material.

In an equi-illumination system, the photocell senses the illumination at a point and results in dimming of one or more luminaires. Where a photocell controls one luminaire it is a relatively simple matter to aim the photocell at a point that is illuminated principally by the controlled luminaire. For group control, location and aiming is not as simple. Locating the photocell at a point illuminated by more than one luminaire is necessary so that one luminaire or one lamp of one luminaire will not unduly influence the photocell output. This is particularly true in spaces where lamps are replaced on an "as needed" basis rather than as a group. It is also particularly true where a single photocell controls a large area consisting of many luminaires. The location of a photo cell in a grid ceiling pttern is also discussed in Section 3.3.4.

Large area zones can also employ a group of photocells which, connected through a common Decision Element, are electronically averaged and provide a single output to a single Control Device.

4.2.2 Presence

Care must be taken in the specification and placement of presence sensors to insure that they will be sensitive only to the intended presence. The manufacturers recommendations for placement are extremely important and should be carefully read prior to writing a specification that identifies the Sensor location. In some cases, particuarly for microwave and ultrasonic presence sensors, it should not be considered abnormal if the sensor has to be relocated after the initial installation because the system cannot be properly nulled.

Because microwaves penetrate walls, the use of multiple microwave sensors in near proximity to each other to control separate lighting systems should be avoided. Ultrasonic sensors must be carefully located with respect to ventilation system components because the transmission of fan noise through ducts or the high velocity movement of air through grills has been known to activate the sensors. Infrared sensors are supposed to be sensitive to the change in radiation received due to body radiation of a human. Some sensors have been known to respond to the heating of a space by sunlight or the cooling by operation of a ventilation system. At least one manufacturer has provided a frequency band pass filter such that only infrared radiation changes at a frequency identified as human will activate the system.

Presence sensors are ideal for conserving energy since they can be used to permit lighting only when it is needed. From the above discussion, however, it is important to conclude that the specification of an appropriate sensor requires care and planning. Manufacturers' specifications should be carefully read and specifications carefully worded to insure that the specific operating conditions with regards to sensitivity, threshold, and space construction including furniture are clearly defined and understood.

4.3 NIGHT/EMERGENCY LIGHTING

Night lighting and emergency lighting are often considered one and the same because the illumination requirements for night lighting will often satisfy any emergency lighting requirements, particularly if the power source for the lighting system is taken from a National Electrical Code recognized emergency source. The two systems are, however, different and should be considered separately in the interest of energy conservation.

A night lighting system satisfies a need to perform certain visual tasks, such as security walk through. It represents a requirement that occurs periodically and can, therefore, be programmed. Night lighting might be required, for example, only between certain hours of the evening and only on certain days of the week. At other times, if the space is totally unoccupied, there may not be a need for any illumination.

An emergency lighting system satisfies a need to perform the visual task of exiting the building safely and represents a requirement that is unpredictable with respect to time and, therefore, unprogrammable. It is necessary for it to respond on the basis of need which is the absence of other lighting as identified by loss of voltage to the normal lighting system.

There are two requirements of an emergency lighting system that distinguish it from a night lighting system.

- Emergency lighting must be capable of reaching full illumination immediately upon identification of need.

- Emergency lighting must be supplied by a source of power that is more reliable than the normal power source.

Consequences of the first item are:

- HID luminaires, in general, are not used where emergency lighting is required without a supplementary incandescent light source, either separate or integrated with the HID luminaire.

- A dimming system cannot be used as an emergency lighting system.

Consequences of the second item:

- A separate wiring system is required from the more reliable source.

• Transfer equipment operated by loss of normal power supply can be used.

The use of a dimming system for both general use and night lighting use is a potentially very efficient design concept. If the system can be dimmed to 2 percent of maximum value, then a nominal 50 footcandle normal use lighting system can be dimmed to 1 footcandle for night use. Because all of the luminaires are in use, the 1 footcandle would be relatively uniform rather than having large pools of light under scattered luminaires.

To meet emergency lighting needs, there are two alternatives. A completely separate emergency lighting system can be used with separate luminaires and separate wiring used only in case of emergency. It should be noted that unless this system is periodically tested, there is no indication that the luminaires (lamps) are in working order.

The second alternative to meet emergency lighting needs is to use selected existing luminaires of the general lighting system (whether dimmable or not), and transfer emergency power to these luminaires in time of need. If the system contains dimming ballasts where removal of control voltage will produce maximum lamp output, then dimming ballasts could be used. A set of contacts on the emergency transfer switch can be used to remove control voltage at the same time that ballast power voltage is transferred from a normal supply to an emergency source of electrical energy.

Figure 4-3 shows an automatic transfer switch (ATS) used in an application of using some general lighting luminaires for emergency lighting. Upon loss of voltage to the Control Device which may be a wall switch, relay, contactor, or dimmer, the automatic transfer switch applies emergency power to the Controlled Element. The Controlled Element is an incandescent lamp, standard ballast, or dimming ballast where loss of control results in maximum output. It should be noted that when transfer to the emergency source occurs, the selected luminaaires for emergency lighting will be energized to maximum lumen output and there will be pools of light under each of these luminaires compared to areas under unenergized luminaires.
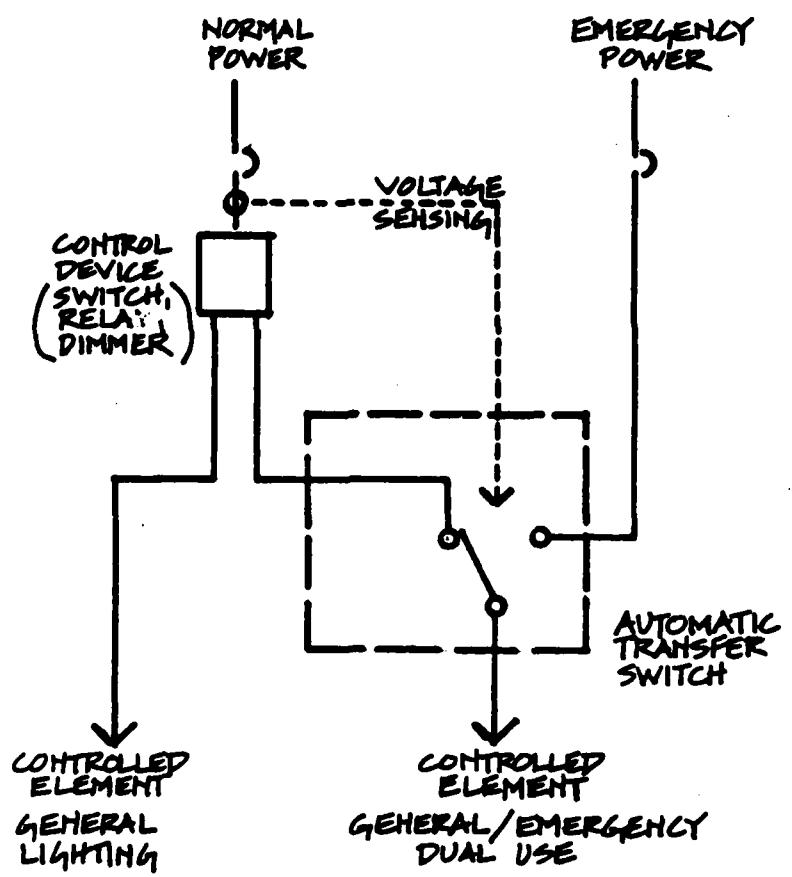
GENERAL LIGHTING LUMINAIRES USED FOR EMERGENCY LIGHTING
FIGURE 4.3

4.4 EFFECT ON OTHER BUILDING SYSTEMS

4.4.1 Air Conditioning/Heating

A lighting system converts electrical energy into light energy and in the process, heat is produced. Essentially all of the electrical energy consumed is converted to heat. The heat is transferred to the surroundings by conduction, convection and radiation. The exact distribution will be different for each luminaire light source type, ceiling installation, air return configuration, etc., and has not yet been determined accurately.

Where the luminaire is installed below the ceiling, all of the heat enters the space. Where the luminaire is recessed in an air return ceiling plenum, it has been estimated that 40 percent of the heat goes into the plenum and the remaining 60 percent goes into the space. Of the heat that goes into the plenum, a portion may be dumped out of the building directly depending upon the percentage of fresh air that is brought in and the remainder remains in the building.

It can be seen from the above that a large portion of the electrical energy used for lighting heats the building. In the summer, additional air conditioning may be required and in the winter, less heating is required than without the lighting system. Typically, it may be estimated that one watt of centrifugal compressor air conditioning power is required to remove the heat of 5 watts of lighting. Similarly, 1 watt of reduced lighting power will require 1 watt of electric heating power.

In determining the economic benefits of a lighting control system, whether dimming or ON/OFF, consideration should be given to the effect of the input electrical energy on both heating and cooling. It is particularly important to take into account the energy source used for heating and for cooling. Where the heating and/or cooling is obtained from steam, there is negligible savings in cooling or additional cost in heating. Where cooling is by electrically driven centrifugal compressors, lighting energy (kilowatt-hours) saved should be multiplied by a factor of 1.1 to 1.2 to determine the total building effect. For electric heating, dimming should not be considered to save energy during the heating season. It should be noted that many new buildings are so well insulated that the latent heat of people and the heat from lighting is more than sufficient to heat the building requiring, therefore, that controlled cooling be provided throughout the year.

ON-OFF control of lighting should not be expected to affect cooling/heating system electrical demand if there is the potential for the lighting system to be ON at a high demand time of day. Turning a lighting system ON or OFF does not immediately affect the cooling/heating system for two reasons:

- Because of building thermal inertia, the heating and/or cooling systems do not respond to instantaneous space heating/cooling requirements.

- Heating and cooling equipment demand requirements are most heavily dependent upon the mechanical control system design and not necessarily on system heating/cooling demand.

An equi-illumination control system will affect the cooling/heating system demand requirements due to the reduced net heat gain from the luminaires. Although the system demand requirements may be reduced, the actual electrical demand of the equipment depends upon the mechanical control system design. If the equipment operates at maximum capacity whenever it is turned ON (perhaps best efficiency), then no reduced electrical demand will result. If, however, a proportional control system is used, then reduction in electrical demand will occur.

4.4.2 Ventilation

Ventilation requirements are typically based upon air change requirements rather than the amount of heating or cooling. Therefore, lighting control should have no effect on ventilation with one exception. When a space is unoccupied, the ventilation requirements are usually reduced. For the particular application where presence sensors are used for lighting control, consideration should be given to use the same sensor to control the ventilation requirements. For example, a two-speed fan could be operated at low speed except when the space is occupied, at which time the fan would run at full speed. This application would be particularly effective where the space is occupied only a few hours each day or when occupied less than once per day.

4.4.3 Security

There are various considerations, often conflicting, with regard to how a lighting control system affects security. Presence sensors are often used to detect unauthorized entry. When presence sensors are also used for lighting control, care must be taken so that the different sensors do not conflict with the operation of each other.

For unattended areas, the presence sensor can be a very effective deterent because the lighting system can be made to

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turn ON with no visible or convenient means of turning OFF.
Thus, intruders are exposed in a lighted environment when
they may prefer to operate in the dark. Systems of this
nature, often referred to as "shock" systems, must use
incandescent or fluorescent sources since an instantaneous
ON is required.

4.5   OPERATIONAL CHARACTERISTICS

4.5.1   User Availability

A control system for energy conservation will only be effective if the operational control is simple to use and readily available to the user. A manual system that has a single switch at the entrance doorway may be more effective than an automatic system that is always bypassed because there is no way to operate the system at unscheduled times. In the former case, if the manual switch is convenient to use and the person using the space is conditioned to turn lights OFF when not in use, then energy will be conserved. In the latter case, if an automatic system turns lights OFF and it is difficult to turn them ON manually by someone wanting to work in the space, then a means will be found to turn the lights ON that may defeat the automatic system operation. Typically, the control voltage is physically disconnected or shut off and the lighting system stays on continusouly, thereby using excessive energy rather than saving energy. Some examples should serve to demonstrate the principle.

A large open plan office space is controlled by a single contactor located in an electrical closet. The contactor is operated by a time clock to turn ON at 0730 and to turn OFF at 1730, five days a week. Housekeeping personnel have been trained how to turn the lights ON and OFF at the contactor using a local manual station. A single employee is behind in his work and comes in on Saturday to work. He locates the contactor, turns it ON, all of the lights go ON although he is working only in a small area, and he proceeds to work. When he is through, he does not turn the lights OFF because the electrical closet is too far from his work station and the lights stay ON until they are shut OFF Monday evening. The addition of more OFF trip signals in the time clock would limit the amount of time that the entire system remains ON. If it is typical that lights are needed in several different locations in evenings and on weekends, then the use of a single contactor may not fit this application. A low voltage switching system with many local switches each of which controls a small group of luminaires may be more appropriate. In this way an individual can easily turn lights ON and OFF at his location and a central time clock can still turn all lights OFF at various times of the evening and weekend. The use of the local switches will keep the occupants from wanting or needing to override the automatic portion of the system.

A presence sensor is used in a four-man office to turn lights ON when someone enters the office. On occasion when only one of the occupants was at his desk, the lights would go OFF and the occupant would have to get up and out of his chair in order to turn the lights ON. As a consequence of this

occurring at inopportune times, the occupant turned sensor
adjustment controls until the lights stayed ON continuously.
This occupant made an adjustment because the lighting system
was not always readily available to him. Relocation of the
existing sensor or the addition of another sensor may have
solved the problem of "availability".   Another possible
solution would be to use a local override switch. To prevent
the override switch from being operated continuously, it
should be automatically reset remotely.

4.5.2   Maintenance Requirements

No system will operate indefinitely without some main-
tenance of repair work being required. Typically solid-state
electronic components require virtually no maintenance. If
failures occur they are usually corrected by component sub-
stitution. Mechanically operated devices wear out, but
for typical operation, quality relays and switches should
last 5 to 10 years. Potentiometers, if continually varied,
may have a shorter life.   Mechanical devices require
occasional cleaning of contacts and/or brushes.

It is significant in the design of a lighting control
system that failure of a single component of the system should
not render the total system unuseable and/or add signifi-
cantly to the electric utility costs. Typically the failure
of a single switch, for example, should render either only a
small portion of the lighting system (small control zone)
unuseable or the entire system should be operable by an
alternate means (perhaps manual instead of automatic, or
local instead of remote).

Failure of a dimming system, if it fails in a full ON or
maximum illumination mode, which is generally the case in
thyristor failures, can have a significant impact on electric
utility costs. An equi-illumination system that has been
maintaining a power input level that is 70 percent of maximum
connected lighting load could increase utility costs for a
full year if it suddenly provided maximum illumination when
the entire building was demanding maximum electric power.
The increase in demand would not only affect the current month
billable demand, but it could also affect the ratchet demand
charge if one exists. It is, therefore, desirable that a
building lighting control system be composed of a number of
lighting control systems for small spaces where the size of
the space is not overly significant with regards to space
usefulness and electrical demand.

For an equi-illumination dimming system, the lumen
output of the lamps and the efficiency of the luminaire
significantly affect the power requirements. Spot replace-
ment of lamps due to burnout and random cleaning of luminaire
reflectors and louvers can grossly distort the performance of
such a dimming system and render it both aesthetically poor

and visually unacceptable. Unless the photocell that measure the illumination at a point in the space senses an illumination that is representative of the entire controlled space, some luminaires will be darker and some brighter than others. Thus, illumination requirements are not met and/or excessive electrical energy is used.

5. ECONOMIC ANALYSIS

5.

5. ECONOMIC ANALYSIS

5.1 GENERAL

Economic analysis is a framework for the systematic investigation of problems of choice. An economic analysis postulates alternative means of satisfying an objective and then systematically investigates the costs and benefits of each of these alternatives. This orderly comprehensive presentation of investment alternatives allows the designer or decision maker to select the most cost-effective option open to him. All economic analysis consists of five steps:

- Establish objectives

- Identify alternatives

- Formulate assumptions

- Determine costs and benefits

- Life-cycle Cost Analysis

Each of the first four steps can be performed to various degrees of presumed accuracy and detail. The extent of detail will depend upon the manner of performing the comparison of Step 5.

The process of comparing costs and benefits is a multi-step process that can be performed manually (by hand calculation) or by computer. The use of a computer increases the accuracy of the calculation because, in general, more specific operating conditions are able to be accounted for in the computer. This is due to the computer's speed of computation, the ability to store and recall reference data, and the logical organization of the input and processed data. There is no fundamental reason why the manual computation could not be expanded to achieve the same accuracy except for time and the patience of the evaluator.

The accuracy of the evaluation depends upon the accuracy of the assumptions and of the input data. In general, in order to save time in a manual evaluation procedure, the assumptions that are made are less rigid and the input data is averaged over longer periods of time. Even the computer calculation is subject to inaccuracies due to finite increments of time and the necessity to predict future operating conditions.

5.2 LOAD PROFILE

The objective of a lighting control system is to provide adequate illumination for the required visual tasks. If a space is unoccupied for a period of time, then there may not be a visual task requiring illumination during that period. A space may also have multiple visual tasks that occur at different times of the day and that require differing amounts of illumination for each task. A description of the illumination requirements for a space, of which there may be many for a building, is conveniently portrayed by a load profile.

The load profile is a histogram of required illumination as a function of time of day. It is desirable to define a histogram for each day of the week because the requirements may be drastically different for groups of days such as weekday and weekend. Although it might be more accurate to include events that occur monthly or annually, a weekly set of histograms is generally considered sufficient. For manual calculations, a simplification to limit the amount of calculation might be to consider two histograms, one for a typical weekday and one for a typical weekend day. The weekday histogram would be considered to apply five-sevenths (5/7) of the total annual days and the weekend histogram would apply to two-sevenths (2/7) of the total annual days.

The required illumination histogram is built up from two possible responses to lighting control: task requirement and occupancy requirement. The task requirement defines the illumination that will be provided by the control system to perform the required visual tasks. The occupancy requirement defines the illumination that will be provided because of the pattern of use of the space. For example, a space or lighting control zone may have a specific visual task but at certain times of the day that task may not be performed due to lunch, breaks, arrival, departure, etc.

For manual analysis, an average illumination may be defined to limit the amount of calculation. Thus, if, for example, an illumination of 70 footcandles is desired nominally from 0700 to 1800 for the visual task but 30 footcandles is required for arrival from 0700 to 0800, lunch from 1200 to 1300 and departure from 1700 to 1800, the demand is 70 footcandles (maximum) and the energy usage is based upon an average of 59 footcandles for 11 hours.
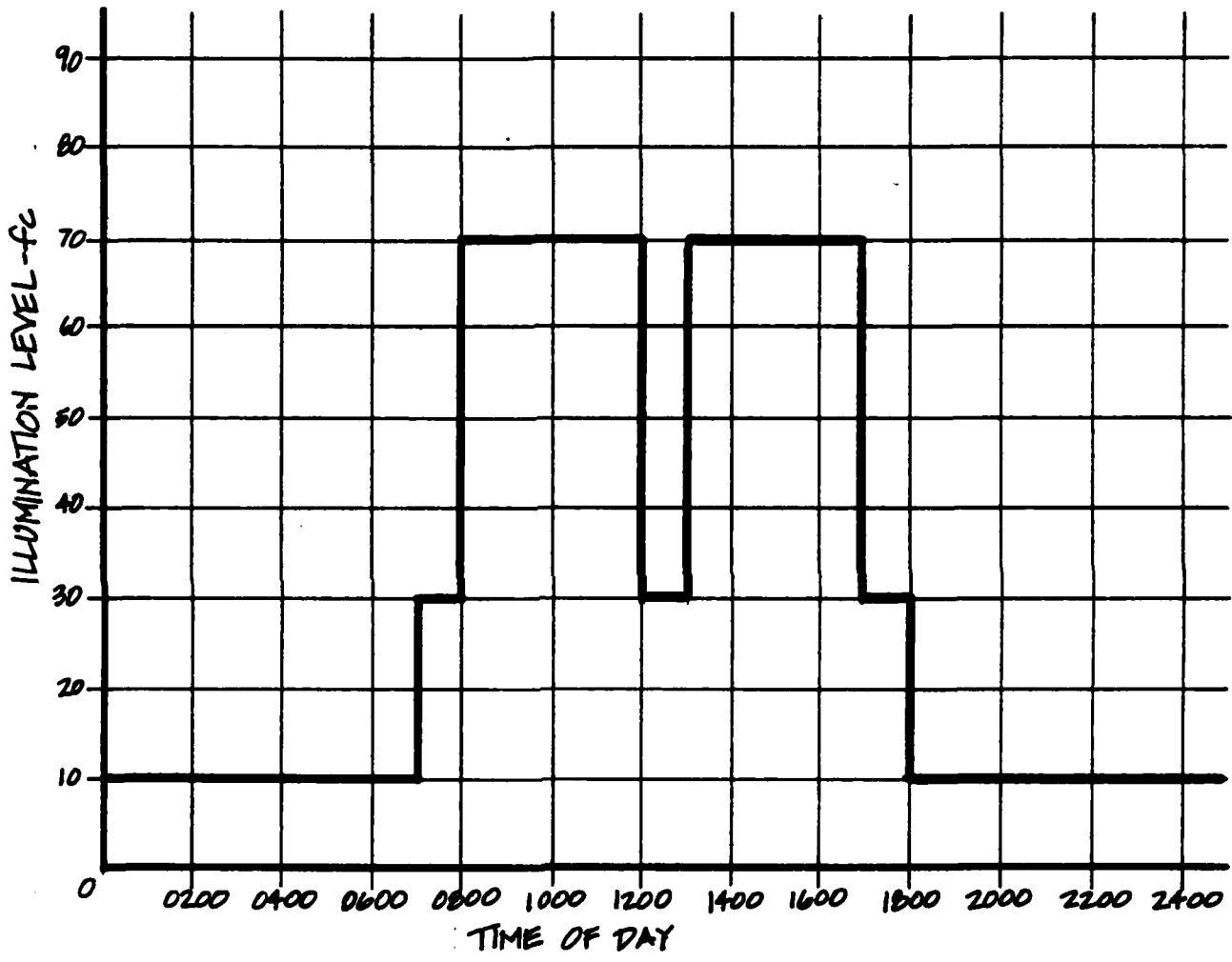
LOAD PROFILE HISTOGRAM
FIGURE 5.1

5.3 ALTERNATIVES

Since the ultimate purpose of economic analysis is to assist the decision maker in allocating financial resources, it is essential that all realistic alternatives be considered. Good decisions are difficult to make without a full understanding of all of the relevant options.

Occasionally there may exist a priori notions concerning the desirability of one of more options or budget restraints that tend to exclude certain alternatives. Such preconditions should in no way inhibit the control system designer from doing a complete analysis. All reasonable and viable alternatives should be considered. Consideration of all alternatives provides useful information about "impossible" alternatives.

A question often arises as to whether an alternative that violates an administrative ground rule, such as initial cost, should be considered if the alternative can be shown to have the lowest life-cycle cost (present value). The answer must be YES because the decision maker should have ALL feasible alternatives available for evaluation and selection. Although the option with the lowest life-cycle cost may not be selected for various reasons, objective and subjective, all parties to the decision process should know the cost of making a specific decision.

5.4 ASSUMPTIONS

Economic analysis deals with future expenditures and, therefore, involves elements of uncertainty. A complete factual description of an alternative may be impossible to define and, therefore, certain assumptions may be necessary in order to proceed with the analysis. Assumptions should be clearly identified for what they are and what they are based on. Some of the assumptions that may have to be made for lighting control system economic analysis follow.

5.4.1 Daylighting Contribution

The characteristics of daylighting, if it exists and can impact on the control system, need to be defined. The daylighting system is characterized by the amount of illumination provided in the lighting control zone. For a computer calculation, the maximum illumination, latitude, facing direction, and clear days will define how the daylight illumination varies by time of day and by season. For a manual calculation, the daylight contribution may be considered as an average value that reduces the average illumination provided by the artificial lighting system.

5.4.2 Lighting System Light Loss Factors

Lighting system light loss factors (LLF), such as Dirt Depreciation and Lamp Lumen Depreciation, define the extent by which the initial lumens of a luminaire decreases with time. Factors to be used are given in the Illuminating Engineering Society Handbook. The assumed operating conditions defining the depreciation factors should be clearly defined.

Depending upon the type of lighting and control system considered, the above depreciation factors may not be used in the analysis. For example, if the lighting system is operated ON-OFF, the power requirements of incandescent and fluorescent luminaires are independent of the age of the lamps and the dirt on the luminaire. For HID lamps, input wattage generally increases with lamp age. If the control system is dimming or equi-illumination dimming, then both depreciation factors will be important in determining input power requirements.

5.4.3 System Efficacy

Input power versus illumination level is a basic characteristic of the lighting system and is similarly used by both computation methods. For manual computation, the relationship may be a curve from which specific operating

points are obtained. For computer computation, a set of points can define the characteristic over the entire operating range and permit incremental values to be used.

5.4.4 Occupancy Schedule

Except for security and aesthetic considerations, illumination is generally not needed unless the space is occupied. A schedule of when the space is generally occupied is important in order to define a nominal usage or base condition. From this base, alternative control schemes can be compared to determine the expected savings.

An occupancy schedule may be fixed or random. fixed schedules are for those spaces that are occupied on a regular basis at given times of the day. For example, a drafting area may be occupied from 0700 to 1500 on Monday through Friday. Since some workers arrive early and some leave late, there may be an additional 30 to 60 minutes fixed occupancy at the beginning and at the end of the above schedule. The illumination requirements for the pre and post
working period may be different than the normal working period. See Section 5.2 and Figure 5-1.

A random schedule may apply, for example, to a person who spends part of his time in an office and part of his time in a laboratory or shop. For an economic analysis, it is necessary to define the average amount of time that the space is occupied. If daylighting is a consideration, then the estimate of time must be determined for increments of time such as: morning, noon time, early afternoon, late afternoon, and evening.

5.5   COSTS AND BENEFITS

All costs associated with design, construction and main-
tenance of the system need to be defined along with the point
in time at which they occur. Typically, design and con-
struction costs occur at the beginning of the economic
evaluation period. It is possible to consider delayed
funding of a portion of construction particularly where
construction funding is limited.

Maintenance costs are defined for items such as lamp and
ballast replacement. Evaluation of group replacement versus
spot replacement is not usually considered as part of an
economic evaluation of a control system. The costs are
typically allocated as a lump sum in the year in which they
occur. An economic evaluation to determine the optimum time
from a total operating cost point of view for lamp replacement
is a valid analysis for defining a maintenance program, but
is beyond the scope of this Handbook.

The cost of energy has been described in Secton 2.6 in a
general manner because each part of the country with a
different utility company will have a different rate
structure with different rates for each billable quantity.
For purposes of evaluation, it is necessary to be specific not
only for the rate in effect, but also for anticipated rate
increases.

Care must be taken in using the appropriate incremental
rate particularly where rates are stepped as a function of
quantity. Both demand and energy rates should be considered
separately. The use of an "average" energy cost obtained by
dividing the monthly utility bill by the total energy usage
is not valid where demand rates apply or where stepped or "on-
peak/off-peak" rates apply. The averaged value does not
adequately account for the savings that might accrue.

As an example, consider a presence detector used to turn
OFF lights in small offices. If it is possible that all
lights will be ON during peak demand, then this control method
has no effect on demand charges. If the percentage of time
that lights will be OFF can be estimated, then a percentage
reduction in energy usage at the applicable time-of-day rate
would apply.

For an equi-illumination dimming system with a daylight-
ing contribution, the demand for the system should be based
upon no daylight contribution. It is possible that peak
demand will occur on a cloudy day with minimal daylight. This
procedure is conservative in that the total savings may be
more than calculated but not less. It should be remembered
that for the given example, the input power (with no daylight

contribution) will increase with time due to Lamp Lumen Depreciation and Dirt Depreciation.

Benefits are often difficult to define and measure explicitly. In spite of the difficulty, it is necessary to quantitatively assess the benefits associated with each alternative whenever possible. A discussion of techniques for benefit analysis is contained in NAVFAC P-442 Economic Analysis Handbook.

5.6   LIFE CYCLE COST ANALYSIS

The basis of Life Cycle Cost Analysis (LCCA) is that two (or more) alternative systems can be compared by the investment that is necessary today (Present Worth) in order to pay for construction and operation costs for the entire life of the system. The comparison can be made only if the two systems meet, as a minimum the same design performance objectives.

Present Worth takes into account the time value of money. Since money is a productive commodity, it commands a price for its use and that price is interest. If a cost occurs in a later year (after construction) due to maintenance or cost of energy, then that cost can be paid for by investing a smaller amount of money today. If the principal plus interest earned is equal to the cost at the later time, then the principal is the present worth of the deferred cost. Life Cycle Cost Analysis is a systematic procedure to account for all of the deferred costs and a means to determine the Present Worth of each of the deferred costs.

There are several factors that are used in Life Cycle Cost Analyses and these factors are generally tabulated as appendices to reference texts. These factors are "discount rate" and "annuity factor". The two factors depend upon the interest rate and differential escalation rate. The interest rate, sometimes referred to as the discount rate, is the cost of money. If money is borrowed for construction purposes, the discount rate is the rate of interest that would have to be paid on the loan. The discount rate is also considered to be the general rate of inflation.

Some commodities, specifically energy costs, may increase on a yearly basis at a rate that is greater than the general rate of inflation. The difference between the two rates is called the "differential inflation rate" or "differential escalation" by some authors.

Once the discount rate and differential inflation rate have been defined, then it is possible to determine the required investment today to pay a future one time cost (discount factor) or the required investment today to pay a fixed annual cost, such as energy or maintenance (annuity factor).

5.7   COMPUTER MODELS

For large systems with complex controls, a computer model may be convenient to more accurately compare alternative control strategies from an economic point of view. Good computer models are not readily available and may be proprietary. An example of an unpublished model is contained in the final report to a contract performed by Smith, Hinchman & Grylls Associates, Inc. for the University of California Lawrence Berkeley Laboratory and submitted for final approval June 1981. The purpose of the contract was to develop a tool to objectively predict the return on investment via energy savings of lighting control systems and strategies. The basis for the computer program is contained in a paper by Mr. Steven Stannard entitled "An Economic Analysis of Supplemental Skylighting for Industrial and Office Buildings," which appeared in the July 1979 issue of the Journal of the Illuminating Engineering Society.

The program can analyze any one of three power input versus light output relationships: continuous dimming with a linear response, continuous dimming with a non-linear response, or discrete stepped response. Any of these options can be used with or without daylighting, and thus, there are six distinct modes of control system operation. A sine series is used to fit the input daylight values over the course of a day. At the user's discretion, more than three values can be used to build the curve.

A complete control scheme for some given space may have up to seven different control days that are assumed to occur each week throughout the year. A control day consists of a unique histogram and an associated energy cost rating block structure for that day. As light output depreciates over time, more power is required to provide a specified value of artificial illuminance, and thus, the maintenance factor plays a part in total energy consumption and the costs associated with it. The effect of maintenance factors is treated for all control system modes except one. In the case of stepped control response where no daylighting is present, the maintenance factor is not considered. Such systems usually respond to a specified power input scheme and stepping to higher levels of light as the system depreciates is not done. Total energy consumtpion values for the solstices and equinoxes serve as the data points to build a curve of yearly energy patterns. From this curve the technique of Fourier series integration can be used to give monthly or yearly values of energy and operating costs. As daylighting conditions can be broken up into clear and cloudy days, a separate curve is generated for each condition and weighting factors on a monthly basis are used to determine the net effect.

The program incorporates a life-cycle cost model to enable the designer to compare different systems on an economic basis. Yearly operating costs are calculated in conjunction with energy consumption values, and the operating costs of the base and controlled systems are known. In addition, initial costs associated with a control system can be specified, as well as a salvage value of the equipment at the end of its economic life. Present Worth and Savings Investment Ratio techniques are employed to give two separate methods of economic comparison of a controlled lighting system against baseline conditions.

6. EXAMPLES

6. EXAMPLES

6.1   GENERAL

This section applies the information of the previous chapters to three example problems: an aircraft maintenance hangar, a warehouse/supply building, and a group headquarters/administrative office building. These examples are based upon simplified assumptions of functional use, task, and occupancy for the purpose of demonstrating the process of control system design. In actual system design, it is necessary to identify the actual or expected use, task, and occupancy and then develop a set of operational histograms following the process outlined here for each alternative.

6.1.1   Site Data

All three facilities are existing buildings located in close proximity of each other in San Diego, California, and are NAVFAC standard construction.

For the purpose of daylighting analysis, as required, the following general data may be established for all three facilities:

- Longitude of site: 117° - 10' West

- Latitude of site: 32° - 45' North

- Pacific Standard Time Zone

- Time increment of 8 time zones west of Greenwich standard

- Average sky conditions

	Percent Clear Sky Days	Percent Partly Cloudy Sky Days	Percent Cloudy Sky Days
January:	42	26	32
February:	39	25	36
March:	36	32	32
April:	34	33	33
May:	29	36	35
June:	30	40	30
July:	42	42	16
August:	48	39	13
September:	50	30	20
October:	48	29	23
November:	50	27	23
December:	45	26	29

(Reference: U. S. Department of Commerce
"Comparative Climatic Data
through 1976")

• Civil Time of Local Sunrise

March 21:	6:20 A.M.	(0620)
June 21:	5:50 A.M.	(0550)
December 21:	7:15 A.M.	(0715)

6.1.2 Utility Data

In general, a Naval facility consisting of offices, warehousing and hangars is typically large enough to warrant purchasing electrical energy at primary supply rates. The rates as described in Section 2.6 would typically include demand charges, on peak/off peak energy usage charges, and power factor penalties. Naval facilities, however, do not normally pay for electricity directly to the local utility, but rather, are provided with electricity from the Public Works Department.

The Public Works Department generally purchases electricity from the local utility at primary supply rates. The average cost of electricity is determined each month by dividing the total electrical bill by the total kilowatt-hours of electricity used. This average rate is then used to bill each of the tenants (Naval facilities) for the total kilowatt-hours used regardless of when the energy was used or what the peak demand was.

The examples in this section are for Naval facilities that are tenants to the Public Works Department. The cost of electricity to be used in analyzing energy conservation investment programs is $0.107 per kilowatt-hour with no separate and additional charge for demand. This energy cost is to be used regardless of the actual average cost of electricity that the facility is paying.

6.1.3 Economic Analysis Factors

The economic evaluation of the example lighting control systems is based upon a Life Cycle Cost Analysis that takes into account the time value of money (present worth). The discount rate and the differential inflation rate may be dictated by the specific funding program being used. For example, Energy Conservation Investment Program (ECIP) dated 27 July 1978 has a 6 percent discount rate and 7 percent differential inflation rate for electricity for the year 1983. For these examples and unless otherwise directed, a discount rate of 10 percent should be used. Differential inflation of 7 percent should be applied only to electricity costs.

The economic life is the period of time over which the life cycle benefits may reasonably be expected to accrue. For a building, the economic life is usually considered to be 20

or 25 years. For controls within the building, an economic life of 15 years is used in these examples and is probably an upper limit due to technological advances in the field of control.

A Savings to Investment Ratio (SIR) is used to evaluate alternative programs. A ratio greater than one indicates that the investment is cost effective over the economic life of the project and is necessary to qualify for funding. Investment is an initial construction cost and occurs at the beginning of the project. The savings occur year after year reduced by any additional maintenance or capital costs that may occur throughout the life of the project. These savings are converted to present worth in order to calculate the Savings to Investment Ratio.

Projects are generally prioritized according to the energy savings achieved for a given capital investment. This insures the most efficient use of capital investment monies. The energy savings-to-investment ratio (E/C) is stated in million Btu's per $1,000 of total investment. The energy savings is in terms of the equivalent energy saved per year at the source of producing the energy. For electricity, a conversion factor of 11,600 Btu/kWH is used to permit standardized project evaluation. This factor represents an efficiency of 29.4 percent in the generation, transmission and distribution of electricity to the point of utilization. To be considered for funding, projects in 1983 had to have an E/C ratio of 18 or higher, and in 1984, the minimum value was reduced to 17.

Projects with quick payback are attractive regardless of how they are funded. Payback is typically determined by the ratio of capital investment to the cost of energy saved per year without regard to inflation. This is termed simple payback and is especially attractive when it is 3 years or less.

6.1.4   Design Objectives and Criteria

The objective of a lighting controls project is to provide an economically feasible means of conserving electrical energy without sacrificing the quality of lighting necessary for task performance. This is to be accomplished by providing lighting only when and where it is needed and only in the required amounts.

To be economically feasible, any proposed system should show a discounted Savings to Investment Ratio (SIR) of at least 1.0.   In addition, an energy savings-to-investment (E/C) ratio of at least 17 million Btu's per $1,000 investment is required in 1984 to be considered for funding under ECIP/ETAP programs. This E/C ratio can also be expressed as 1,466 kWH per $1,000 investment.

6.2 EXAMPLE 1 - AIRCRAFT MAINTENANCE HANGAR

6.2.1 Design Assumptions and Restrictions

The facility in this example is an aircraft maintenance hangar. The gross area for a typical facility is 39,000 square feet, comprised of 20,000 square feet of hangar space (51 percent of the total), 22.5 percent of shop and storage space, 22.5 percent of office space, and 4 percent of "mezzanine" circulation space (4 percent of the total). The building is oriented such that the Front Elevation (hangar doors) face directly to the South.

Electrical requirements indicate that 63 percent of the building lighting power is expended in 51 percent of the total area. The greatest potential to conserve electrical energy in lighting appears to be in the hangar area. This example will limit itself to the hangar area, since techniques for conservation in the other types of spaces will appear in the other examples. In actual project design, however, consideration to the conservation opportunities in all spaces should be made.

The available funding for renovation is assumed to be limited, therefore, replacement or major modification to the existing lighting and electrical systems is not considered to be feasible.

The lighting system for a 100-foot by 100-foot hangar space consists of 400 watt, 50,000 lumen, High Pressure Sodium (HPS) lamp sources in industrial high bay luminaires with standard Auto-Reg ballasts. Each ballast, operating at an input circuit voltage of 277 volts, consumes 475 watts of power, at a power factor of 0.90, input current being 1.9 amps. The system consists of 64 luminaires, for a total maximum demand of 30,400 watts (3.04 watts per square foot).

The electrical system distributes power at 277 volts to 8 circuits of 8 luminaires each. The existing lighting and branch circuit layout is shown in Figure 6-1. Typical voltage drop at the luminaire is 3 percent.

The existing system provides no controls for lighting, except for panelboard switching of 20 amp circuit breakers (8 luminaires per group as shown in Figure 6-1). These breakers, some 10 years old, are not rated "SWD" (see Section 2.4.2).

6.2.2 Functional Analysis

The first step is a determination of the usage of the space, both in terms of function and operational schedule of that function.

N ←

400 W. HPS
(TYP.)

PRESENT
CIRCUITING

OPEN
HANGAR
DOORS

12'-6"
(TYP.)
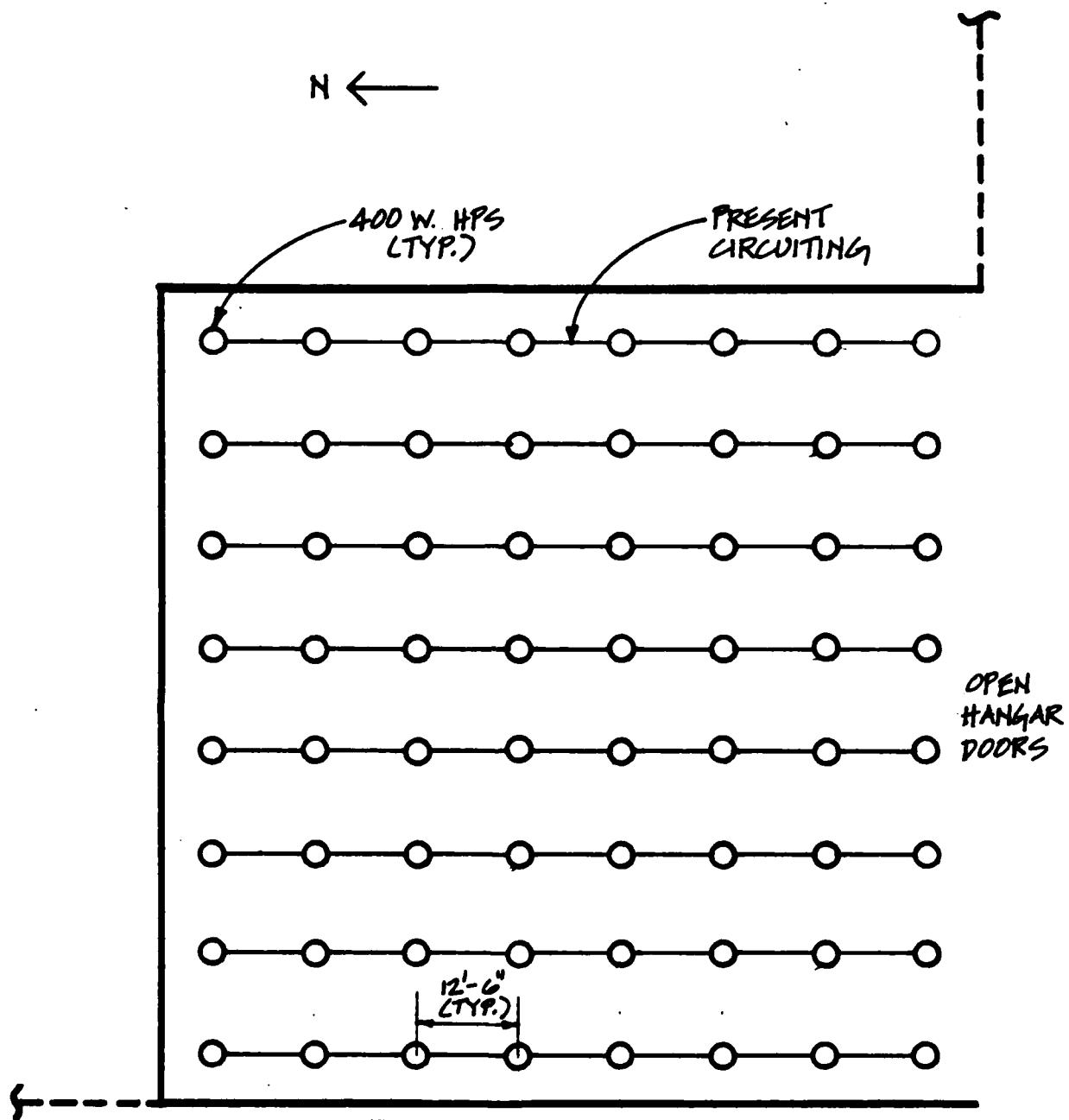
HANGAR LIGHTING PLAN
FIGURE 6.1

The hangar is assumed to be used primarily for maintenance functions, although aircraft may also be stored inside when space is available. Hangar doors are kept open during daylight hours from May 1 to October 1. Maintenance functions include repairs to airframe, power plant, avionics, and hydraulic systems, as well as periodic inspections of all operating systems.

Aircraft are assumed to occupy a space approximately 30 feet by 50 feet and generally six aircraft will be located in each hangar (three in line front-to-back). It is possible for storage purposes to put nine aircraft into a hangar, but then the other maintenance/ repair/inspection functions would not be performed under those conditions.

Since the hangar space is large compared to the size of the aircraft, aircraft can be maneuvered and are located at prescribed locations within the hangar. Movement in and out of the hangar may require one hour total time. At least one aircraft is moved out and one moved into the hangar in each weekday period. Preparation of aircraft for maintenance activity generally requires 8 hours at the beginning and an additional 8 hours to restore all systems, plates, etc. at the end of the activity. Airframe repair, if it occurs, generally requires 16 hours of continuous work. Inspection, whether it is of the difficult or highly difficult type, occurs intermittently during the first 24 hours after initial preparation and the final 24 hours that includes the restoration activity.

6.2.3 Visual Task Analyses

Evaluation of the illumination requirements for each of the visual tasks is obtained from the IES Lighting Handbook, 1981 Application Volume, Chapter 9 - Industrial Lighting. The principal visual tasks and the illumination requirements are:

- Security   10 fc

    This task occurs whenever any of the activities below are not in progress

- Docking - moving aircraft in and out   50 fc

    Docking is performed from a towing vehicle by a driver at a 5-foot level above floor. It is necessary for the driver to be assured that the aircraft being moved will not strike an object in the space. Typically, at least one observer watching on the floor is assisting him.

- Preparation of aircraft for mainten-
  ance/repair/inspection activity and
  restoring all preparation activities   75 fc

  This activity typically occurs from floor level up
  to an elevation of 15 feet, and may require the setup
  of 10-foot high platforms. Exceptions may occur
  where airframe repair is required to 20 feet.

- Remove and reinstall components   75 fc

  This activity occurs from floor level to an ele-
  vation of 15 feet.

- Airframe repair   100 fc

  Airframe repair can occur from 3 feet to 20 feet
  above the floor.

- Inspection - difficult   100 fc

  This activity occurs from floor level to 20 feet
  from floor level.

- Inspection - highly difficult   200 fc

  This activity occurs only between 3 and 10 feet from
  the floor level.

6.2.4   Occupancy and Use Analyses

Operations in this facility are on a two shift, five day
per week basis for maintenance and repair. On the weekends,
there are two shifts and only minor maintenance is performed.
The first shift is from 0700 to 1530 and the second shift is
from 1500 to 2350.

There is no set pattern for lighting requirements
because of the differing repair times for each aircraft.
During the typical 8 days that each aircraft is in the hangar,
lighting is required for each aircraft for the following
typical average hours:

10 fc	146 hours
50 fc	2 hours
75 fc	24 hours
100 fc	16 hours
200 fc	4 hours

A histogram showing the typical use and illumination
requirements for one airplane is given in Figure 6-2.
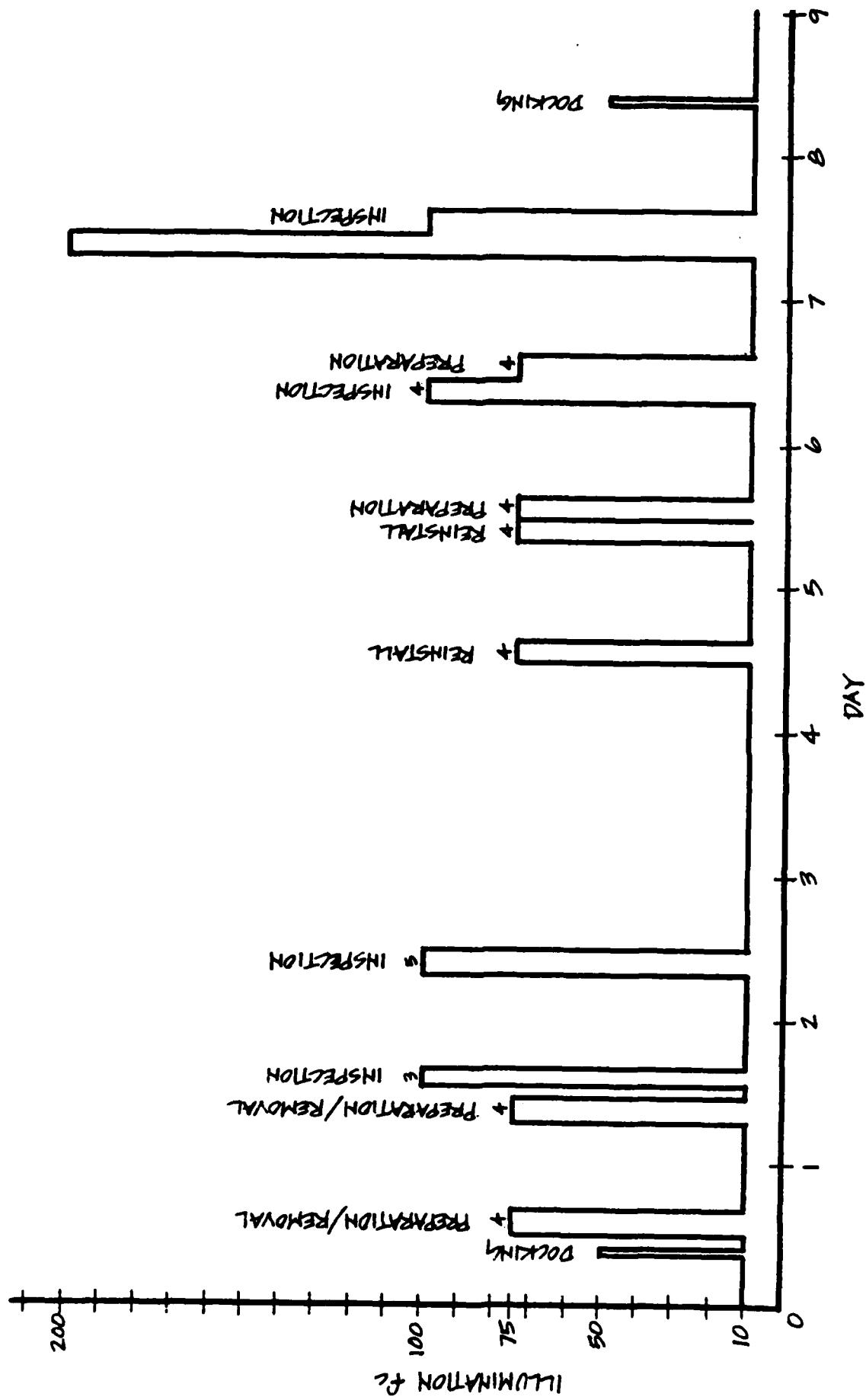
TYPICAL AIRCRAFT MAINTENANCE HISTOGRAM
FIGURE 6.2

6.2.5 Maintenance Analyses

In an effort to improve the performance of the lighting system, a new maintenance program will be instituted. This program was devised independently of the control project, is funded separately, and assumes current practices of operation, which includes all lamps burning for approximately 8,000 hours per year.

The maintenance program includes cleaning all luminaires once every year, group replacement of all lamps once every two years, and repainting the interior of the hangar space every six and one-half years. Spot replacement of lamps will occur only if it is deemed that the affected zone is critically in need of the replacement.

From manufacturers' published data for lamps, and referring to the 1981 IES Lighting Handbook Reference Volume, Section 9, the following Light Loss Factors can be tabulated:

- Lamp Factors

	Lamp Lumen Depreciation	Lamp Mortality
100 hours	1.0	1.0
4,000 hours	.98	.97
8,000 hours	.95	.93
12,000 hours	.90	.86
16,000 hours	.84	.76
20,000 hours	.79	.63
24,000 hours	.73	.49

- Luminaire Factors

	Luminaire Dirt Depreciation
0 year	1.0
0.5 year	.92
1.0 year	.87
1.5 years	.83
2.0 years	.79
2.5 years	.76
3.0 years	.73

- Room Factors

	Room Surface Dirt Depreciation
0 year	1.0
0.5 year	.99
1.0 year	.98
1.5 years	.97
2.0 years	.96
2.5 years	.95
3.0 years	.94

	Room Surface Dirt Depreciation
3.5 years	.93
4.0 years	.92
4.5 years	.91
5.0 years	.90
5.5 years	.89
6.0 years	.88
6.5 years	.87
7.0 years	.86
7.5 years	.85
8.0 years	.84

Applying these factors to the maintenance program, a profile is developed assuming that lamps are burning 8,000 hours per year. This profile is plotted in Figure 6-3.

	Recoverable Light Loss Factor
0 year	1.0
0.5 year	.87
1.0 year	.75 - .87
1.5 years	.69
2.0 years	.53 - .96
2.5 years	.83
3.0 years	.72 - .83
3.5 years	.66
4.0 years	.51 - .92
4.5 years	.79
5.0 years	.69 - .80
5.5 years	.63
6.0 years	.49 - .88
6.5 years	.76 - .87
7.0 years	.76 - .87
7.5 years	.70
8.0 years	.54 - .97

6.2.6 Estimation of Existing Electric Lighting System Performance

In order to assess the impact of controls upon the visual environment, an estimation of the available electric lighting must be made. Since the system has been poorly maintained to date, actual field measurements of existing conditions will be deceptive. However, field measurement of reflectances is strongly recommended for retrofit projects.

LIGHT LOSS FACTORS AND TOTAL LIGHTING SYSTEM PERFORMANCE
FIGURE 6.3
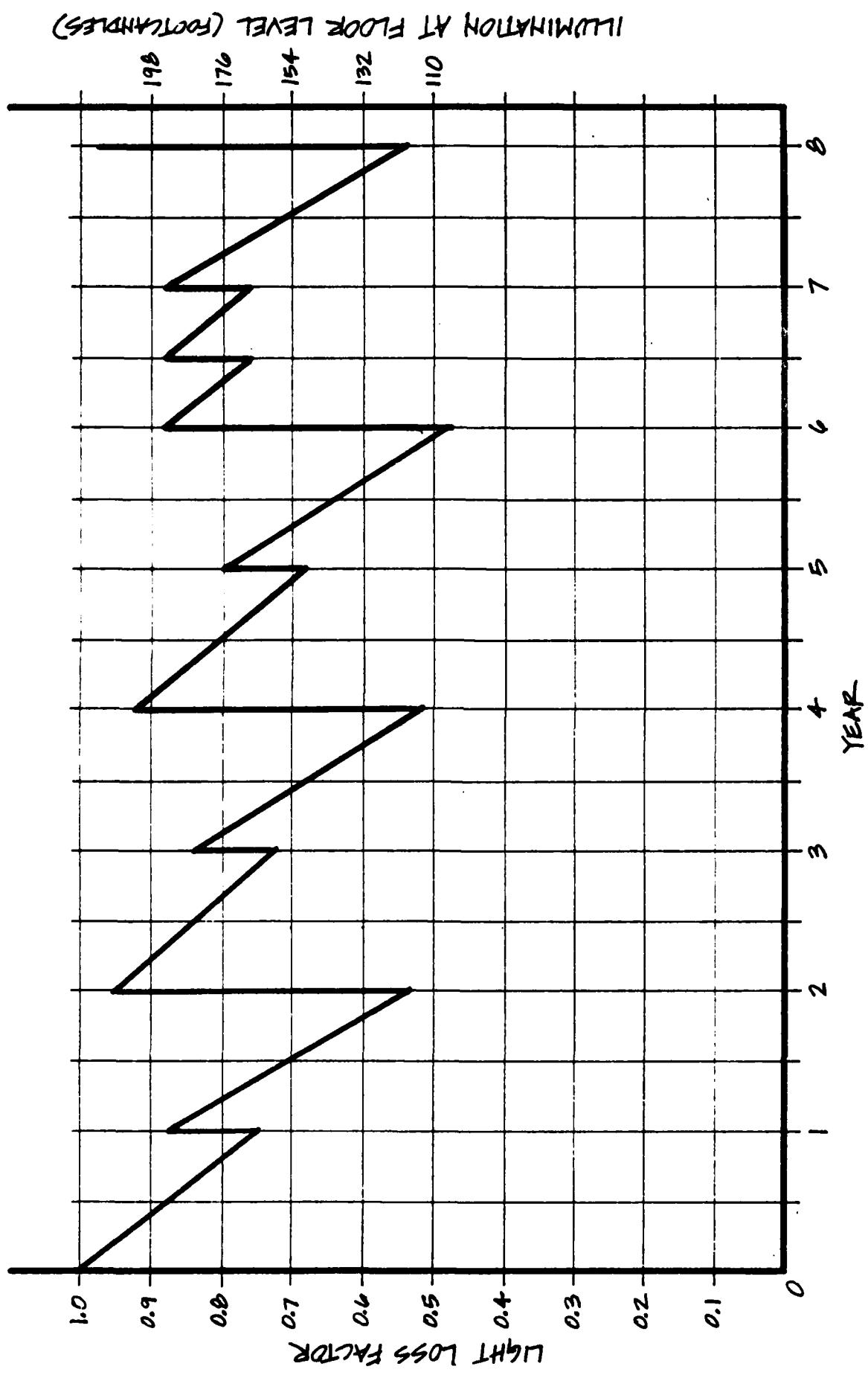
As part of the new maintenance program outlined in
Section 6.2.5, a complete and thorough cleaning of all
luminaires and a complete system relamping should be per-
formed at this time. This will bring the system to within 5
percent of its initial operating state. Maintenance of the
lighting system is essential to efficient performance. Refer
to Section 6.2.5. The cost of this maintenance is not
considered to be part of the renovation, and, therefore, is
budgeted separately.

Estimates of the illumination levels, after the above
maintenance has been performed, provide a revised "initial"
lighting level. Calculations can be performed using Zonal
Cavity Average Illuminance techniques or by computer simu-
lation (such as LUMEN II or LUMEN Micro). For this applica-
tion, the Zonal Cavity technique is considered adequate.

In order to simulate the revised "initial" conditions,
a multiplying factor for the non-recoverable Light Loss
Factors must be applied (in the normal mathematics for Light
Loss Factors). Since the reflectance values have been
determined by field measurement, these factors include the
voltage drop and luminaire surface depreciation. Ambient
temperature and ballast variation are not significant
factors in this application. The factor for this applica-
tion, therefore, is 0.92.

Zonal Cavity calculations indicate that a uniform spac-
ing of 64 luminaires within the 100-foot by 100-foot by 28-
foot cavity will provide, after the initial maintenance, an
average initial horizontal illumination level of 221 foot-
candles at the floor plane. At 10 feet above the floor, the
average "initial" horizontal illumination level is indicated
to be 240 footcandles.

Applying the Recoverable Light Loss Factors from
Section 6.2.5, the profile of horizontal illumination levels
at the floor plane is made. It is shown in graph form in
Figure 6-3. For horizontal illumination at 10 feet above the
floor, the illumination at the floor should be multiplied by
a factor of 1.09. This factor is obtained by dividing the
average illumination at 10 feet (240 footcandles) by the
average illumination at the floor plane (221 footcandles).

6.2.7 Estimation of Available Daylight

In the functional analysis (Section 6.2.2), it is
observed that the hangar doors remain open during daylight
hours. It is possible though that they may not be kept open
during inclement weather. For this example, a computer
simulation using LUMEN II was used to determine the day-
lighting contribution within the hangar at various times of
the year and times of day.

A criterion of 75 footcandles is selected to cover the illumination requirements of more than one half of the activities on a typical airplane. It is apparent that supplemental lighting will be required at least for certain inspection tasks. Using this criterion, the results of the computer daylighting simulation is tabulated in Table 6-1 in terms of the distance into the hangar from the doors at which at least 75 footcandles exist. A sample computer run is shown in Table 6-1A for May 1 (Spring), 1,600 hours (afternoon), and cloudy sky with no electric lighting and hangar doors open. The Y coordinates are from front to back with zero being the hangar doors.

It is apparent from the above tabulation that the amount of electric supplemental illumination in the daytime is highly dependent upon the amount of cloud cover and somewhat dependent upon the time of day.

6.2.8   Control Zones

As defined in Section 1.2, a lighting control zone is a functional area that has common lighting requirements and common control opportunities. For this example, it has been determined from the functional analysis that there are six areas generally denoting the location of six airplanes that are being serviced. Although it is possible to store nine airplanes in the space, storage is not the primary purpose of the space, nor the major activity in terms of hours of use of the hangar. From a functional area point of view, there should be six control zones, three on each side of the hangar with the division down the center. From front to rear, there should be three zones with three rows in the front and rear zone. The middle zone should ideally have four rows, two of which are common to the front and rear zone, respectively.

Each of the six airplane locations is a functional area with a common lighting requirement. From the Estimation of Available Daylight, there is a common control opportunity based upon the amount of daylight available. Depending upon the amount of cloud cover and the time of year, the requirement for electric lighting will vary from front to rear of the hangar. It would, therefore, be most desirable from a daylighting point of view if the control zones are individual East-West rows.

A desirable circuit loading for the existing fixtures is eight per circuit. This will result in a circuit load of 15.2 amperes at 277 volts. For a 20 ampere circuit breaker that can be loaded to 80 percent of rating, or 16 amperes, this circuit load is the maximum possible. For a 30 ampere circuit breaker, twelve fixtures are the maximum number on one circuit, however, replacement of the wiring with larger ampacity conductors would be required.

Table 6-1

DISTANCE FROM DOORS IN FEET AT WHICH 75 fc AVERAGE
IS AVAILABLE ON A CLOUDY/CLEAR DAY

	Morning	Noon	Afternoon
Spring/Fall	50/100	55/100	25/60
Summer	65/100	65/100	35/70

ILLUMINATION

Table 6-1A
SAMPLE COMPUTER RUN FOR DAYLIGHTING

WORKING PLANE HEIGHT: 0.

AVERAGE: 63.384   MINIMUM: 13.157   MAXIMUM: 255.128   MEAN DEVIATION: 50.673

ABS. Y COOR.	ABSOLUTE X-COORDINATE(S)																		
	5.0	10.0	15.0	20.0	25.0	30.0	35.0	40.0	45.0	50.0	55.0	60.0	65.0	70.0	75.0	80.0	85.0	90.0	95.0
95.0	13.5	13.9	14.3	14.6	14.8	15.0	15.2	15.3	15.4	15.3	15.4	15.3	15.2	15.0	14.8	14.6	14.3	13.9	13.6
90.0	13.2	14.0	14.2	14.5	14.7	14.9	15.0	15.1	15.2	15.2	15.2	15.1	15.0	14.9	14.7	14.5	14.2	14.0	13.2
85.0	13.8	14.3	15.0	15.2	15.4	15.6	15.8	15.9	16.0	16.0	15.9	15.9	15.8	15.6	15.4	15.2	15.0	14.3	13.8
80.0	14.8	15.3	15.8	16.3	16.6	16.7	16.9	17.0	17.1	17.2	17.2	17.0	16.9	16.7	16.6	16.3	15.8	15.3	16.8
75.0	15.9	16.5	17.0	17.4	17.6	18.0	18.2	18.4	18.5	18.6	18.6	18.4	18.2	18.0	17.6	17.4	17.0	16.5	15.9
70.0	17.5	18.1	18.7	19.3	19.7	20.2	20.4	20.5	20.7	20.7	20.7	20.5	20.4	20.2	19.7	19.3	18.8	18.1	17.5
65.0	18.9	19.6	20.4	20.9	21.4	21.8	22.3	22.5	22.6	22.6	22.6	22.5	22.3	21.8	21.4	20.9	20.4	19.6	18.9
60.0	21.2	22.1	23.0	23.8	24.4	24.9	25.4	25.8	26.0	26.0	26.0	25.8	25.4	24.9	24.5	23.8	23.0	22.1	21.2
55.0	24.2	25.3	26.5	27.5	28.4	29.1	29.6	29.9	30.3	30.4	30.3	29.9	29.6	29.1	28.4	27.5	26.5	25.3	24.2
50.0	27.0	28.5	29.9	31.1	32.2	33.0	33.6	34.0	34.4	34.7	34.4	34.0	33.6	33.0	32.2	31.1	29.9	28.5	27.0
45.0	32.0	34.1	36.1	37.7	39.1	40.1	41.0	41.6	42.1	41.9	42.1	41.6	41.0	40.1	39.1	37.7	36.1	34.1	32.0
40.0	37.6	40.2	42.7	44.9	46.6	48.0	48.9	49.7	49.9	50.1	49.9	49.7	48.0	48.0	46.6	44.9	42.7	40.2	37.6
35.0	45.6	49.4	52.9	55.6	57.9	59.7	61.0	61.5	62.1	62.1	62.1	61.5	61.0	59.7	57.9	55.6	52.9	49.4	45.6
30.0	55.6	61.1	65.5	69.2	71.9	74.1	75.3	76.1	76.8	76.8	76.8	76.1	75.3	74.1	71.9	69.2	65.5	61.1	55.6
25.0	70.0	77.6	83.7	88.3	91.8	94.0	95.5	96.4	97.1	97.1	97.1	96.4	95.5	94.0	91.8	88.3	83.7	77.6	70.0
20.0	89.4	100.3	108.4	114.4	118.0	120.5	122.2	123.0	123.7	123.8	123.7	123.0	122.2	120.5	118.0	114.4	108.4	100.3	89.4
15.0	117.5	133.1	144.0	150.3	154.4	157.0	158.5	159.4	160.0	160.0	159.4	158.5	157.0	154.4	150.2	144.0	133.1	117.5	
10.0	155.4	177.5	188.6	194.9	198.5	200.7	201.9	202.5	203.1	203.0	203.1	202.5	201.9	200.7	198.5	194.9	188.7	177.5	155.4
5.0	215.0	237.8	246.5	250.7	252.7	253.9	254.5	254.8	255.1	255.1	255.1	254.8	254.5	253.9	252.7	250.7	246.5	237.8	215.0

Considering the visual task requirements and the existing electric lighting system performance, Figures 6-2 and 6-3, it would be desirable to operate only half of the lighting most of the time to obtain a minimum illumination of 75 footcandles. For the "security" function, only one fixture per airplane zone is necessary. For "difficult inspection", all fixtures per airplane zone would be operated, and for "highly difficult inspection", supplementary lighting is required in addition to all fixtures being operated.

From the above considerations, one possible distribution of control zones for the existing luminaires is shown in Figure 6-4 and consists of four fixtures to a zone. The assumed space for six airplanes is shown. The indicated arrangement provides for individual low and high level lighting control for each airplane with some overlapping into an adjacent zone. No provision has been made for security lighting.

6.2.9 Potential Control Systems

The potential control systems to be considered are:

- Local ON-OFF

- Equi-illumination

- Daylight sensor for front rows

- Time clock

- Carrier control

- Presence detection

Local ON-OFF control has a definite advantage over the present control (panelboard switching) system. The present system requires 32 fixtures to be operated even when only one airplane is being worked on. With ON-OFF control of the zones indicated in Figure 6-4, either 8 or 16 fixtures can be operated to give a low or high level of illumination at one airplane.

The concept of equi-illumination would be advantageous if the high pressure sodium (HPS) lights could be dimmed. From Figure 6-3, it can be seen that with all lights on, the lighting levels are well above 100 footcandles. (For "difficult inspection", supplemental lighting should be used to obtain 200 footcandles at the task.) With half of the lights on, the lighting level will be well above 75 footcandles (150 footcandles on Figure 6-3). Unfortunately, as stated in Section 3.2.7, at the present time there are no feasible dimming systems for HPS because the lamps become unstable and produce significant color shifts.

-138-
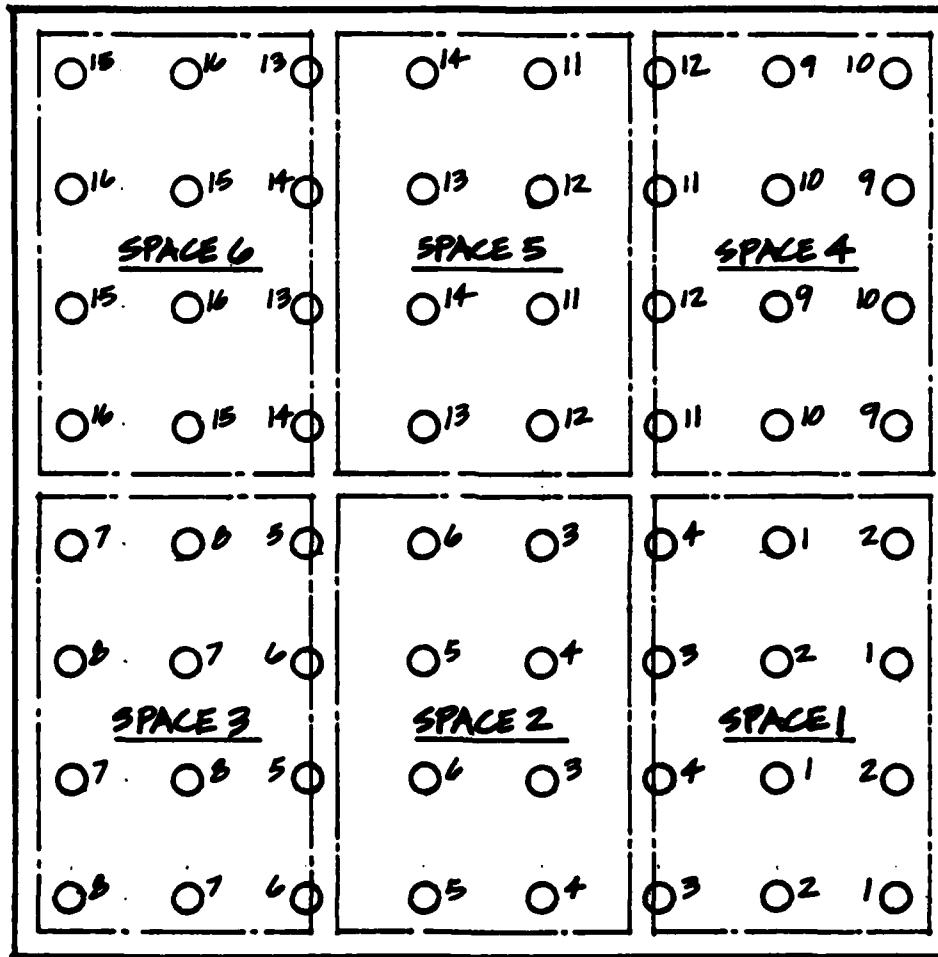
LIGHTING CONTROL SPACES
FIGURE 6.4

From Table 6-1 it appears that daylighting can provide some or all of the necessary lighting at certain times of the year. Daylight sensors would be advantageous in permitting sections of the electric lighting system to be shut off. Since daylighting at times can provide 75 footcandles throughout the entire hangar, it may be advisable to use daylight sensors for each pair of rows (two zones) shown on Figure 6-4. It should be noted that 75 footcandles on the floor may not give adequate illumination ten feet above the floor on the airplane due to the cutoff of daylighting by the top of the hangar door frame.

A time clock has an advantage when functions are based upon time of day. Since there is no third shift, a time clock could be used to turn off all lights at the end of the second shift. This would insure that lights were not left on when not needed. In addition, since only minor maintenance is performed on weekends, a time clock can insure that the 100 footcandle level for inspection and airframe repair is not left on.

The existing conduit system, as shown in Figure 6-1, cannot be used to provide the control zones shown in Figure 6-4. Even if the conduit system is 3/4 inch permitting 11 conductors of No. 12 AWG with THHN insulation to be pulled in, it is doubtful that the junction boxes, located at each fixture, will be of sufficient size to comply with National Electrical Code (NEC) Article 370. Thus, either new conduit is required or a carrier control system using the existing wiring must be provided. The choice should be based upon the total installed cost.

In principle, a presence detection system should have application in this example because if there is no one at the airplane, then there is no requirement for illumination other than for security. There are several reasons why a presence detector is not applicable in this specific example:

- Someone inside the airplane would not be detected and the lights would be shut off.

- Each time an airplane is moved into place the change in reflection could require an adjustment of the five other presence detectors.

6.2.10 Savings Analysis

From the previous section, the following is concluded.

- The system shall have two levels of ON-OFF control for each zone. One level will provide for one-half of the fixtures to attain a minimum 75 footcandles. The second level will operate all of the fixtures.

- A daylight sensor will be provided for each pair of rows for each half of the hangar.

- A time clock shall be provided to turn off all lights after the second shift.

- Replacement of the conduit system will be compared in cost to a carrier control system.

- Equi-illumination and presence control will not be used.

Each shift consists of 8-1/2 hours per day. For the two operating shifts there are 6,205 hours per year. If all lights are operated during the two shifts and 6 lights are operated during the night for security, the annual energy used would be:

$$\frac{475}{1,000} \text{ watts } (64 \times 6,205 + 6 \times 2,555) = 195,916 \text{ kWH}$$

Two control systems are considered, each with a different cost and a different energy savings. Control Scheme A responds to the lighting requirement given in Section 6.2.4 by providing full lighting when 50 footcandles or more are required and one light per aircraft when 10 footcandles are required. Control Scheme A would have the following annual energy usage:

$$\frac{475}{1,000} \times (64 \times 6,205 \times \frac{46}{192} + 6 \times 6,205 \times \frac{146}{192} \times 6 \times 2,555) = 65,925 \text{ kWH}$$

Control Scheme B is a more selective system that provides full lighting only for inspection, half lighting for 50 and 75 footcandles requirements, and one light for security. This system would have the following annual energy usage:

$$\frac{475}{1,000} (64 \times 6,205 \times \frac{20}{192} + 32 \times 6,205 \times \frac{26}{192} + 6 \times 6,205 \times \frac{146}{192} + 6$$

$$x \ 2,555) \ = \ 53,150 \text{ kWH}$$

Except for the security lighting, the remaining lights are on for an average of 2,100 hours per year. Instead of group replacing lamps every two years, the period can be extended to six or six and one half years to coincide with the repainting schedule. The savings in lamp replacement costs is:

$$\frac{(64 - 6) \times 2}{6 \text{ years}} \quad x \quad \$35 \quad = \quad \$677 \text{ per year}$$

No savings in labor is considered because it is assumed that the replacement occurs at the same time as the cleaning.

In order to determine the energy savings that will result by the use of daylight sensors, it is necessary to determine how much electric lighting is not needed during the period when the hangar doors are kept open. The amount of electric lighting that is on will be zero, 25 percent, 50 percent, 75 percent, or 100 percent of the total because of the size of the control zones. Table 6-2 is a tabulation of the percentage of time that the sky is clear, partly cloudy, and cloudy for each of the five months, and the amount of electric lighting that must be on during the morning, noontime, and afternoon in order to maintain a minimum 75 foot-candle lighting level.

Considering only Control Scheme A, a summation of the electrical lighting requirements with daylighting compared to the non-daylit condition yields a savings of 69.1 percent for the first shift. Only one half of this savings is achievable because only half of the hangar is used by the first shift. The second half of the hangar is used by the second shift and only requires security lighting during dayshift hours.

Energy saved during the first shift per year:

$$\text{luminaires} \times \frac{\text{watts}}{\text{luminaires}} \times \text{hours} \times \text{\% hours} \times \frac{\text{kW}}{\text{watt}} \times \text{\% savings} = \frac{\text{energy}}{\text{savings}}$$

$$\frac{64}{2} \times 475 \times \frac{6,205}{2} \times \frac{46}{192} \times \frac{1}{1,000} \times 0.691 = 7,804 \text{ kWH}$$

For the second shift, the Table 6-2 column titled AFTERNOON is considered to apply for one half of the shift with full electric lighting being required for the second half of the shift. A summation of the electric lighting requirements yields a 48.8 percent savings when the hangar doors are open.

Energy saved during second shift per year:

$$\frac{64}{2} \times 475 \times \frac{6,205}{2} \times \frac{1}{2} \times \frac{46}{192} \times \frac{1}{1,000} \times 0.488 = 2,290 \text{ kWH}$$

A control system (Control Scheme B) that responds to the lighting requirements of each task and maintains a minimum security level at non-working periods can save a maximum of

Table 6-2

ELECTRIC LIGHTING REQUIREMENTS
WHEN DOORS ARE OPENED

Month	Sky Condition	Percentage	Percentage Electric Lighting Required		
			Morning	Noon	Afternoon
May	Clear	29	0	0	50
	Partly Cloudy	36	25	25	50
	Cloudy	35	50	50	75
June	Clear	30	0	0	50
	Partly Cloudy	40	25	25	50
	Cloudy	30	50	50	75
August	Clear	48	0	0	25
	Partly Cloudy	39	25	25	50
	Cloudy	13	50	50	75
September	Clear	50	0	0	50
	Partly Cloudy	30	25	25	50
	Cloudy	20	50	50	75

142,766 kilowatt-hours per year. At a cost of $0.107 per kilowatt-hour, the savings would be $15,267 per year. In addition, the savings in lamp replacement should also be included.

A control system similar to Control Scheme B that can also respond to the daylight available when the hangar doors are open can save, in addition, a maximum of 10,094 kilowatt-hours. At the above cost of energy, the savings would be $1,080 per year.

6.2.11 System Cost

It has been indicated in Section 6.2.9 that the present conduit system cannot provide the quantity of conductors necessary for the control zones. If Control System B is selected, the number of conductors per conduit will increase by approximately 50 percent.

Two methods are considered to implement the control systems. The first alternative is to remove the existing conduit and replace with new conduit. The cost is approximately as follows:

1,200	feet 3/4 inch conduit	$5,800
6,000	feet No. 12 AWG THHN	1,400
12	single pole switches	550
4	conductors	2,000
		$9,750

The second alternative is to retain the existing conduit system and add a carrier control system (see Section 3.2.4.4). One receiver is required at each fixture, and two switches for each circuit within a zone. In addition, a remote panel and a coupling device between phases are necessary. Conduit and wire is necessary for new local switches. It should be noted that a carrier system could be added while the facility operates using the existing installation. No down time is necessary. The cost is approximately as follows:

64	receivers	$4,800
16	transmitters (2 switches ea.)	1,500
1	three-phase coupler	100
1	control panel	700
300	feet 3/4 inch conduit	1,200
600	feet No. 12 AWG THHN wire	150
		$8,450

The cost for illumination sensors to detect the need for electric lighting is approximately $3,000. In addition, a receiver and transmitter would be required for each zone. The total cost is approximately $4,000.

6.2.12 Economic Evaluation

Two control systems are considered for evaluation. The first system, called Task Lighting Control, will utilize Control Scheme A implemented with conduit. If Control Scheme A is viable, then Control Scheme B is also viable because the savings are greater with a very small additional cost and the carrier control system will also be viable because of its lower cost.

The second system, called Daylighting Control, assumes that Task Lighting Control has been implemented. By separating the daylighting control from overall lighting control, it is possible to evaluate the economic incentive to various degrees of additional sophisticated control.

ECONOMIC ANALYSIS

Aircraft Hangar
Task Lighting Control

Investment

1. Project Costs (Economic Life of 15 Years)

a.	Construction cost	$ 9,750
b.	Design cost	$ 2,000
c.	Total project cost	$ 11,750

Savings

2. Annual Electricity Savings: kWH $130,000

a.	Equivalent energy: kWH x 0.0116	1,508 MBtu
b.	Cost per kWH	$ 0.107
c.	First year annual dollar savings	$ 13,910
d.	Present worth factor	12.278
e.	Discounted savings	$170,787

3. Annual Other-than-Energy Savings

a.	Labor	0
b.	Material	$ 677
c.	Total	$ 677
d.	Present worth factor	7.980
e.	Discounted savings	$ 5,402

4.	Total First Year Annual Savings	$ 14,587
5.	Total Discounted Savings	$176,189
6.	SIR - Discounted Savings/Investment Ratio	14.99
7.	Simple Payback Period	3.75 mo.
8.	E/C Ratio	331

ECONOMIC ANALYSIS

Aircraft Hangar
Daylighting Control

Investment

1. Project Costs (Economic Life of 15 Years)

a.	Construction cost	$ 4,000
b.	Design cost	$ 1,000
c.	Total project cost	$ 5,000

Savings

2. Annual Electricity Savings: kWH $ 10,094

a.	Equivalent energy: kWH x 0.0116	117 MBtu
b.	Cost per kWH	$ 0.107
c.	First year annual dollar savings	$ 1,080
d.	Present worth factor	12.278
e.	Discounted savings	$ 13,261

3. Annual Other-than-Energy Savings

a.	Labor	0
b.	Material	0
c.	Total	0
e.	Present worth factor	0
f.	Discounted savings	0

4.	Total First Year Annual Savings	$ 1,080
5.	Total Discounted Savings	$ 13,261
6.	SIR - Discounted Savings/Investment Ratio	2.7
7.	Simple Payback Period	4.6 yrs.
8.	E/C Ratio	23.4

6.2.13 Recommendations

The Economic Analysis of the preceding section indicates that the Task Lighting Control System should be implemented for the following reasons:

- Simple payback period less than four months.

- E/C ratio of 331, almost 20 times higher than the minimum requirement of 17.

The specific method of implementation, whether by conduit and wire or with a carrier system, should be determined during the design.

The Daylighting Control System meets the criteria for funding. Because the simple payback period is greater than three years, other energy conservation programs with faster payback should be considered.

6.3 EXAMPLE 2 - WAREHOUSE

6.3.1 Design Assumptions and Restrictions

The facility in this example is a warehouse. The gross area is 9,000 square feet and its dimensions are 150 feet long by 60 feet wide. The building is oriented so that its long dimension is in the north-south direction. One third of the warehouse is office space and is not being considered in this example.

The actual warehousing space is 100 feet long by 60 feet wide with a 14-foot ceiling height. There are 4-foot aisle spaces every 12 feet as shown in Figure 6-5. A 12-foot wide by 88-foot long skylight is located above the center aisle.

The lighting system consists of two lamp, 8-foot long slimline luminaires, surface mounted on the ceiling and aligned generally in the center of each aisle. Each ballast operates at an input circuit voltage of 277 volts, consumes 161 watts of power at a power factor of .95, and an input current of 0.61 amps. The system consists of 62 luminaires for a total maximum demand of 9,982 watts (1.66 watts per square foot).

The electrical system distributes power at 277 volts to circuits of 8 or 9 luminaires. Luminaires are controlled from the panelboard using the circuit breakers. Lights are turned "ON" when the first person arrives in the morning and "OFF" at the end of the workday.

6.3.2 Functional Analysis

Orders are taken in the warehouse office for items that are stored in the warehouse. Assembling an order requires an average of 15 minutes per order and an average of 10 orders are filled and picked up each day. Assembly of an order typically requires material from three aisles after which the order is left at one of the two loading docks for pick up. Delivery of new material for storage in the warehouse occurs twice a week. Unloading and storing on shelves takes an average of four hours for each delivery.

6.3.3 Visual Task Analysis

The principal visual tasks and the illumination requirements are:

- Security   5 fc

    This task occurs whenever any of the activities below are not in progress.

OFFICE AREA

LOADING DOCK
(TYP.)

SLIMLINE
(TYP.)

STORAGE
(TYP.)

SKYLIGHT
ABOVE
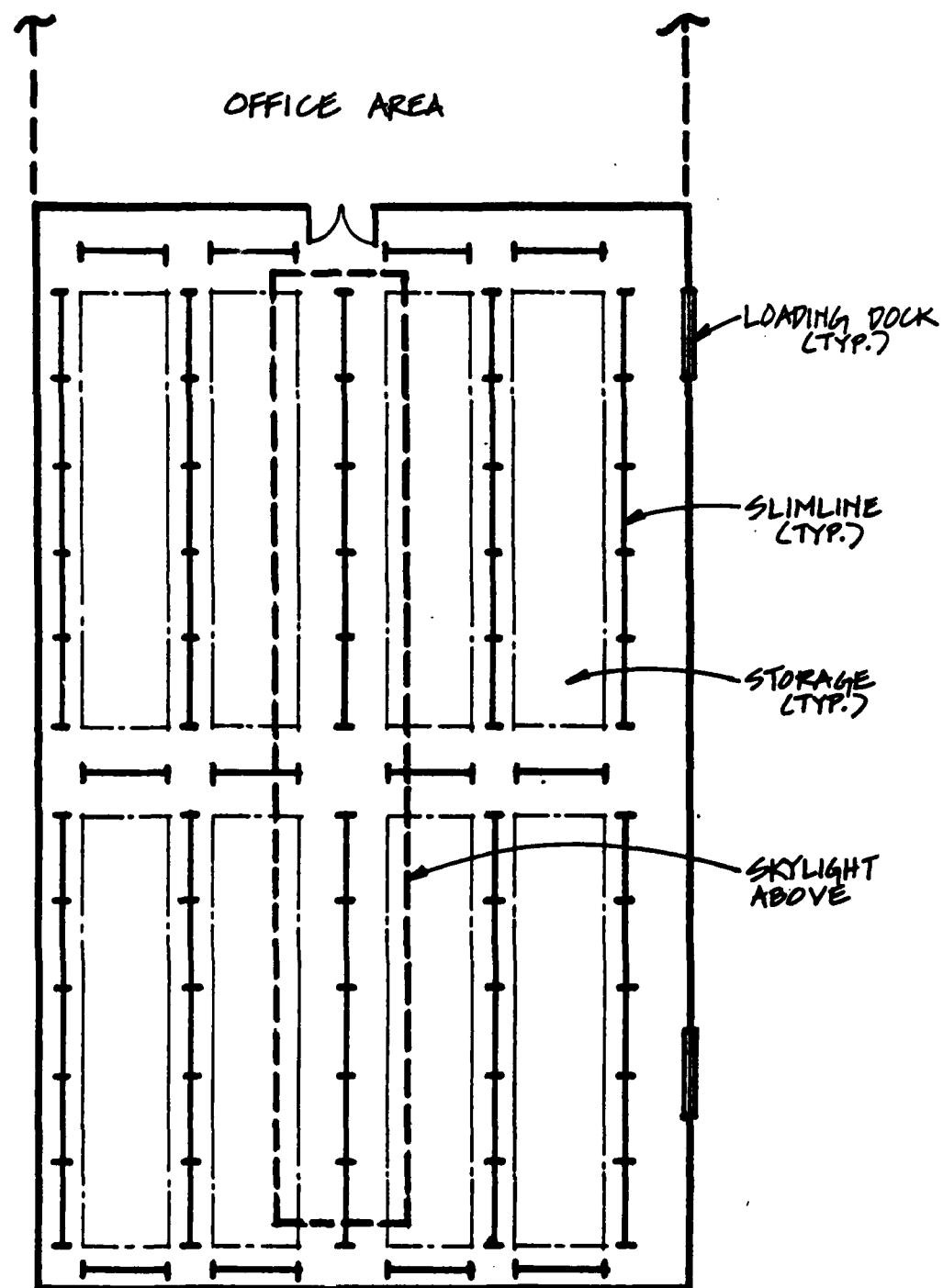
WAREHOUSE PLAN
FIGURE 6.5

- Movement of Hi-Lo   25 fc

  The Hi-Lo is used to assemble an order and also to store new material that has arrived at the loading dock.

- Loading dock activities   25 fc

  This task involves unloading material from a truck and loading it on to a Hi-Lo. In addition, orders are left at the loading dock for pick up.

- In and out movements from the shelves   25 fc
                                              vertical

  Identification markings located vertically on the shelving must be read in order to identify materials. Many of the bins are small requiring the reading of 1/4 or 3/8 inch high black lettering on a matte white background.

6.3.4   Occupancy and Use Analysis

Operations in this facility are on a 0700 to 1530 basis, five days per week. The warehouse is closed on weekends but may be opened for emergencies. One person operates in the warehouse for assembly of orders and unloading. When neither of these activities are in process, the warehouse is vacant and the worker is in the office.

The average lighting requirements for each day are:

5 fc   4.4 hours

30 fc horizontal and vertical   4.1 hours

It should be noted that the vertical illumination requirement exists only at the shelves that are in the process of being loaded or unloaded.

6.3.5   Maintenance Analysis

Maintenance is performed whenever 20 percent of the lamps have failed. Due to the sharp cutoff of the shelving, there is little spillover of light from one row to the next. Consequently, any greater amount of failure would not provide sufficient illumination to read the shelf identification markings.

When maintenance is performed, all lamps are replaced and all luminaires are cleaned. There are approximately 2,500 burning hours per year for the lamps in this warehouse. At this rate, the 20 percent failure occurs at the end of the fourth year.

Without any cleaning in the interim period, the average illumination just prior to lamp replacement would be 45 percent of the initial value (lamp lumen depreciation x luminaire dirt depreciation x room surface dirt depreciation x fraction of operating lamps). The worst factor above is the Luminaire Dirt Depreciation which has a value less than 70 percent at the end of the four years. In order to maintain lighting levels without increasing the initial lumens, it is advisable to clean the lamps and luminaires at least every two years.

6.3.6 Estimation of Existing Electric Lighting System Performance

Calculation of the existing electric lighting system performance can be made using Zonal Cavity Average Illuminance or by computer simulation. For this example, a computer simulation using the LUMEN II program was made in order to identify both the horizontal illumination on the floor for operation of the Hi-Lo as well as vertical illumination on the shelves available to read the identification markings.

The computer simulation indicates an initial horizontal illumination at floor level of 55 to 60 footcandles. The vertical illumination at the shelves is indicated in Table 6-3.

6.3.7 Estimation of Available Daylight

The skylight represents 17.6 percent of the warehouse ceiling. Because of the location and configuration of the skylight and the height of the shelving that serves to cut off light from adjacent aisles, the skylight may be effective only in the center aisle. An analysis of the available daylighting indicates that there is sufficient illumination from the skylight during daylight hours regardless of the sky cloud condition. The only period of time when the illumination may be marginal is in the early morning in December on a cloudy day. By 1000 hours, the illumination is not marginal under any sky conditions. It should be noted that the above conclusions are based on a clean skylight.

6.3.8 Control Zones

The functional areas in the warehouse are the aisles between shelves. The warehouse worker must have sufficient visibility in whichever aisle he may be. Since a particular order may not involve travel in each of the aisles, one possible configuration for control zones is to make each aisle a separate zone. In this way, it would be possible to illuminate only those aisles that are in use at the time. Thirteen control zones would be required.

Table 6-3

VERTICAL ILLUMINATION

Vertical Distance from Floor ft.	Vertical Illumination fc
12	158.7
10	91.8
8	60.7
6	51.5
4	44.2
2	38.5

An alternative approach is to consider that the warehouse is either in use or it is not in use. When no orders are being filled or picked up or when no new material is being delivered, the warehouse space is empty and no illumination (except possibly for security) is required. This approach considers the entire space as one zone.

A desirable circuit loading for the existing fixtures is 22 to 25 two-lamp fixtures per 20 ampere circuit. The lower figure is for standard slimline ballasts and the higher figure is for energy saver type. For this installation, three circuits would be required. The number of circuits and the number of control zones are independent of each other unless panelboard circuit breakers are used to control each zone.

6.3.9 Potential Control Systems

The potential control systems to be considered are:

- Local ON-OFF.

- Daylight sensor for middle aisle.

- Time clock.

- Presence detection.

- Equi-illumination.

Local ON-OFF control has a definite advantage over the present panelboard switching system. With local ON-OFF control, lights could be turned ON when entering the warehouse space and turned OFF when leaving. In addition, if there is a separate switch for the loading dock area, it is possible that only loading dock lights might be turned "ON" when unloading a delivery vehicle or during a pick up of an order.

A time clock could be used to insure that lights are turned "OFF" at the end of the day. If personnel are directed properly, this equipment may not be necessary. In addition, if the site is patrolled by security guards, the guards could be directed to turn lights "OFF".

Equi-illumination control systems may have some merit because the initial illumination is approximately two times the illumination requirements of the visual tasks. Thus, initially the system could dim the lights to one-half while just before lamp replacement, the system would require full output due to the various lumen depreciations. Thus, if the lumen depreciation is assumed to be linear with respect to time for simplicity of analysis, the approximate savings is 25 percent of the total energy usage.

For purposes of this example, it is assumed that a presence detector can be located on a wall at each end of an aisle and can "see", by proper focusing, 40 to 50 feet down an aisle.

6.3.10 Savings Analysis

From the previous section, the following control systems should be considered:

- ON-OFF manual control at entrance to warehouse.

- Presence detector to turn lights "ON" in an aisle only when someone is in the aisle.

- Dimming system to maintain required illumination when illumination is desired. This system should be considered both with and without the presence detectors.

- Daylight sensor for middle aisle only.

Operation of all lights for the entire workday plus one-half hour at the beginning of the day and one-half hour at the end of the day will use 24,656 kilowatt-hours of electricity per year. At the electricity rate of $0.107 per kilowatt-hour, the annual cost of electricity for the warehousing function is $2,638.

The use of ON-OFF manual control has the potential to save 5.4/9.5 or 57 percent of the electricity usage. The potential to save this 14,053 kWH per year depends upon the inclination of the worker to turn OFF lights every time that he leaves the warehouse and goes to the office. The savings could be anywhere from zero to the above maximum value.

A presence detector sensing in each aisle would operate a maximum of 805 watts of luminaires at any one time. Since there would probably be some overlap of lighting zones, it is assumed that the average usage will be increased by 20 percent to a maximum of 966 watts. The potential savings is:

$$24,656 \ - \ \frac{966 \times 4.1 \text{ hrs. } \times 260 \text{ days}}{1,000} \ = \ 23,626 \text{ kWH}$$

An equi-illumination system, as previously described, can save approximately 25 percent of the average energy usage. Thus, the annual savings for the previous systems are as follows:

- Existing system   12,328 kWH

- Manual ON-OFF (depending
  upon whether lights are
  actuall turned "OFF"
  manuall)   5,301 kWH to
                                                 12,328 kWH

- Presence detector   515 kWH

The daylight sensor for the middle aisle would have the following annual savings:

- Existing system   1,996 kWH

- Manual ON-OFF   862 kWH to
                                                   1,966 kWH

- Presence detector   84 kWH

6.3.11 System Cost

From the previous Savings Analysis, the control system based on the presence detector has the greatest potential for saving electricity. For purposes of this example, only the presence detector system will be analyzed. It is recongized, however, that other control systems such as the equi-illumination system may be more advantageous economically because of a shorter payback period even though the total savings are less.

It is assumed that the present conduit system is adequate and only small additions to the conduit system are required. The estimated costs are:

13 sensors at $300	$3,900
200 feet 1/2 inch conduit	700
1,000 feet No. 12 AWG	250
	$4,850

There is a potential for additional lamp replacement costs because of the number of times each day that the luminaires will be turned "ON". Because of the typical low failure rate at the end of four years when lamp replacement would probably occur, no additional costs are included.

6.3.12 Economic Analysis

ECONOMIC ANALYSIS

Warehouse
Presence Detection Control System

Investment

1. Project Costs (Economic Life of 15 Years)

a.	Construction cost	$ 4,850
b.	Design cost	$ 1,000
c.	Total project cost	$ 5,850

Savings

2. Annual Electricity Savings: kWH $23,626

a.	Equivalent energy: kWH x 0.0116	275 MBtu
b.	Cost per kWH	$ 0.107
c.	First year annual dollar savings	$ 2,528
d.	Present worth factor	12.27
e.	Discounted savings	$30,838

3. SIR - Discounted Savings/Investment Ratio   5.3

4. Simple Payback Period   2.3 yrs.

5. E/C Ratio   46.8

6.3.13 Recommendations

The Economic Analysis factors determined in the previous section are all favorable for implementing the Presence Detection Control System for the warehouse. The Discounted Savings to Investment Ratio (SIR) is much greater than unity indicating that the investment is cost effective. The energy savings to investment ratio (E/C) is 2.75 times greater than the minimum of 17 and, therefore, represents efficient use of capital investment monies. Finally, the simple payback period of 2.3 years makes this investment especially attractive.

In view of the above positive factors and the fact that the control system savings are automatic and independent of what the warehouse worker does, it is recommended that this control system be implemented.

6.4 EXAMPLE 3 - OFFICE

6.4.1 Design Assumptions and Restrictions

The facility in this example is a two-story office building that contains a mixture of one-man offices and open landscape offices. The building is 100 feet long by 60 feet wide with 8-foot ceiling height. Windows on the north and south sides cover 40 percent of the vertical surface and 20 percent on the east and west sides.

The example space is 60 feet long by 22 feet wide with 6-foot high partitions. The resultant offices are approximately 8 feet by 8 feet. One long wall faces south and has windows over 40 percent of the wall surface.

The lighting system consists of four lamp, 40 watt, 2 by 4 fluorescent fixtures with a standard prismatic lens in a lay-in ceiling. The fixture grid is 6 feet by 8 feet. Each ballast operates at an input circuit voltage of 277 volts, consumes 96 watts of power at a power factor of 0.96, and an input current of 0.36 amps. The system in the example space consists of 30 luminaires for a total demand of 4,760 watts (4.4 watts per square foot).

The electrical system distributes power at 277 volts to circuits of up to 22 luminaires each. For this example, it is assumed that the luminaires are on two circuits and that the lights are turned "ON" from the panelboard.

A plan of the example space is given in Figure 6-6. The location of the luminaires are shown as well as the 6-foot high partitions.

6.4.2 Functional Analysis

The office space is used for the preparation of reports and graphic material for training classes. Extensive use is made of computer terminals which are located at random in half of the offices. Data is both inputed to and read from the terminals.

6.4.3 Visual Task Analysis

There are two principal visual tasks. One task consists of reading and writing pencil on paper and reading xerox and typewriter copy. The illumination requirements are typically 50 footcandles. Although the government has never adopted equivalent sphere illumination (ESI), its use in this application is preferred because it is a measure of ability to see (visibility). With the ESI footcandle as a metric, the illumination requirement would be 40 ESI footcandles. In

WINDOWS THIS SIDE

6 FOOT HIGH PARTITION (TYP.)

4-40 W. FLUORESCENT (TYP.)
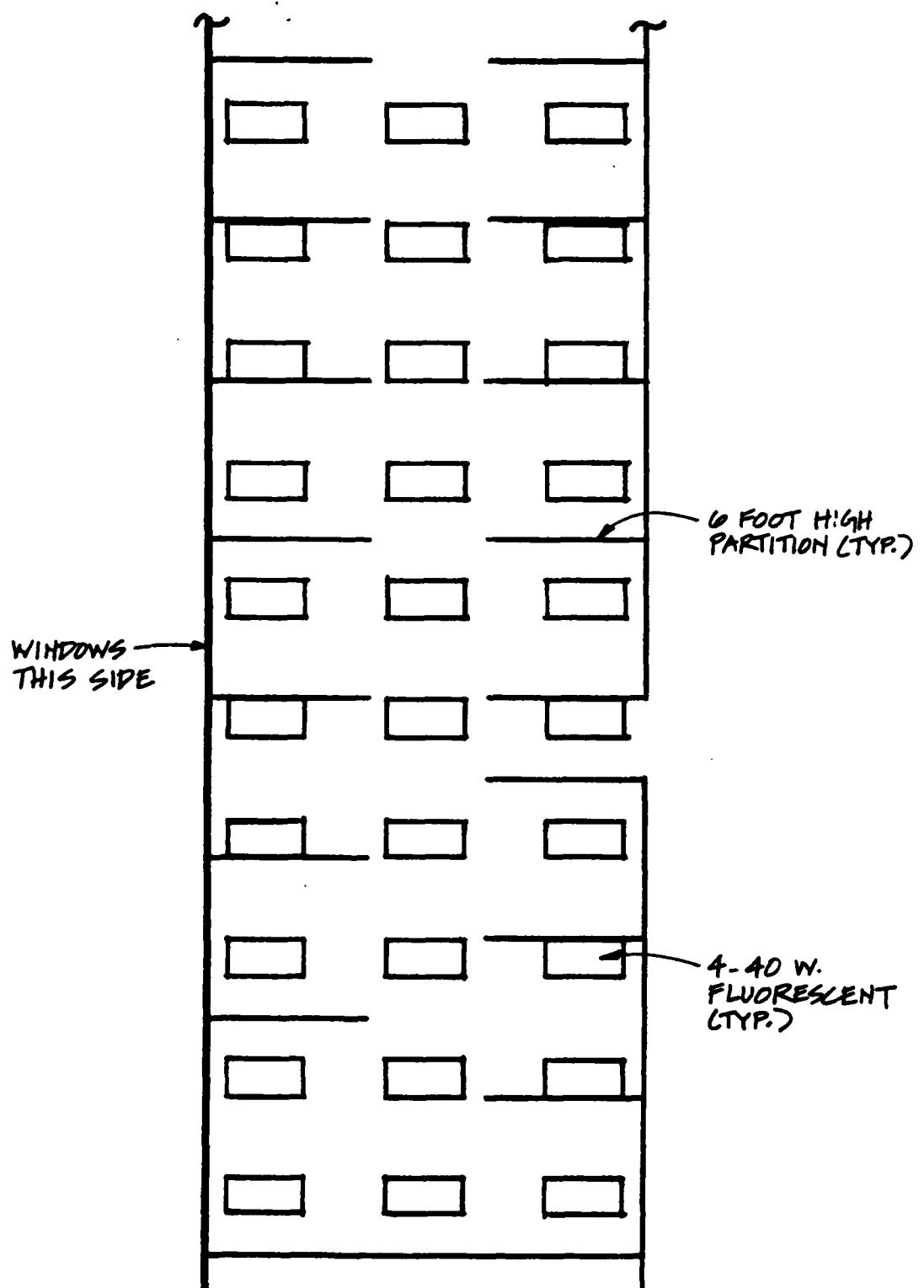
OFFICE PLAN
FIGURE 6.6

general, the careful use of a metric for illumination that is related to contrast will result in a properly designed lighting system which operates at a lower raw footcandle level.

The task of reading data from a computer terminal is best performed at a background illumination of 5 footcandles with no visible reflection from other luminaires. Where the use of the terminal is only for short periods, the task can also be performed with higher illumination levels. Regardless of the illumination level, reflections from other luminaires or windows tend to veil the screen data and make it unreadable.

6.4.4   Occupancy and Use Analysis

The normal hours of use of this facility are from 0800 to 1700 from Monday through Friday. Arrival of employees is a maximum of 30 minutes before the starting time and departure may be up to 30 minutes late. Occasionally employees, on an individual basis, will work during an evening or on the weekend. Lunch is generally from 1200 to 1300, however, the space remains somewhat occupied because some employees eat at their desks.

Due to the nature of the training material being pre-pared, half of the employees travel and are not in their offices every day. On the average, 20 percent (3 offices) are vacant each day.

6.4.5   Maintenance Analysis

Lamp replacement and luminaire cleaning is performed on a spot or "as needed" basis. Lamps are replaced whenever two lamps of one luminaire fail. At that time, the luminaire is also cleaned. Lamps are also replaced if one lamp flickers.

The above maintenance procedure results in less than 50 percent of initial lumen output being available just prior to lamp failure (and lamp replacement).

6.4.6   Estimation of Existing Electric Lighting System Performance

Calculation of the existing electric lighting system performance is made using Zonal Cavity Average Illuminance. In this calculation, it is assumed that there are no parti-tions. Using this method, the average initial illumination is 140 footcandles.

Because of the partitions, the lighting is not uniform in each office. Offices with two luminaires in the office space (See Figure 6-6) will have the above illumination level but with glare. The glare is due to the relative location of luminaire and desk. Relocation of luminaire and/or desk may

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alleviate the problem. Since this Handbook is devoted strictly to controls, no further discussion is made here on how to improve the quality of illumination.

6.4.7 Estimation of Available Daylight

An analysis of the available daylighting has been made using a LUMEN II computer simulation. With the southern exposure as specified, the available daylighting is not useable because of magnitude and contrast.

Daylighting at the windows will provide 125 to 2,000 footcandles depending upon the time of day, the season, and the cloud cover. Illumination in excess of 500 footcandles occurs in the winter all day and in the fall during the morning and noon hours. With illumination of that mangitude, it is probable that some means will be used to reduce the intensity.

Where daylighting results in 125 to 400 footcandles, the illumination drops below 50 footcandles typically within 5 to 7 feet of the window. Thus, wi hin an office located at a window, the illumination due to daylighting may not be sufficient at certain desk locations even though it is two to three times more than required at others. At best, the use of daylighting to reduce the use of electric lighting is only applicable in the first 5 to 7 feet from the window. It would be difficult to estimate the amount of savings without knowing the specific room arrangement and the subjective considerations of the occupant to shade the daylight.

Daylighting has an application to reducing electric lighting usage when it is provided at the right place. The conditions that warrant its use are very restrictive and rarely occur in sufficient quantity to justify a control system specifically for that purpose. Northern exposure tends to produce a more uniform illumination without the extremes of direct sunlight. Eastern exposures are also generally considered good because the direct sunlight is usually cut off by the building during early morning hours resulting in relative uniformity.

Unless specific architectural features are designed as part of the building to project daylight into the building, daylight is only effective in the first 5 to 7 feet from the window. In order to be able to utilize daylight without disturbing occupants that are located in the interior of the building, it is desirable that the outer offices or work spaces be separated by walls or partitions from the inner spaces. In this manner, the outer, private office illumination should be controlled separately from interior lighting control zones.

6.4.8 Control Zones

There are three basic configurations for control zones depending upon the type of control system to be implemented. The most versatile zone configuration is for each office to be a separate zone with the line of fixtures in the center corridor being one of several zones. This configuration permits taking advantage of the fact that not all employees are at their desk every day. Because some offices have two luminaires in the space and some have only one and depend upon adjacent offices for illumination, it is doubtful whether advantage can be taken when an employee is not at his office.

If it is desired to take advantage of daylight, then all or several of the fixtures closest to the windows should be a single zone. From the Estimation of Available Daylight, it appears that there is often an overabundance of illumination. Therefore, it is probable that some means, such as drapes, will be used to block the light. For purposes of this example, daylighting will not be considered.

If it is desired to reduce the illumination provided by the existing lighting system to the requirements of the task, then the selection of zones will be dependent upon circuiting and sensor location. It is valid to consider the entire space as one control zone regardless of the number of circuits supplying the luminaires. Either one or several sensors (connected to provide the average illumination) could be used to control the dimming system. Since there may be a large difference in illumination from adjacent luminaires due to the assumed maintenance procedure, the average illumination has a very low probability of being at the optimum value. Under illumination or over illumination is the more probable condition statistically. Over the long term life of the control system, the average illumination and, therefore, the energy saved will be as set by the control system.

To improve the uniformity, it is necessary to increase the number of control zones each with its own sensor or sensors. If each zone had one luminaire and one sensor, then a more uniform lighting system would result. The system may not be cost effective due to the high cost of construction.

For purposes of this example, it is initially assumed that there are five zones of six luminaires each and that each zone has two averaging sensors. Other configurations and sensor quantities and locations should be investigated to determine the best economic choice. It should be noted that the size of the control zones and the locations(s) of the sensor(s) must also fit the functions that are performed in the space.

6.4.9 Potential Control Systems

The potential control systems to be considered are:

- Local ON-OFF with time clock.

- Equi-illumination.

A local ON-OFF control system using low voltage relays or a carrier system can take advantage of the fact that three offices are vacant each day. The system would use a time clock to shut off all lights at the end of the day. Lighting for each office would be turned "ON" by each occupant. Lighting in the center aisle would be turned "ON" by the first person to arrive at one of the offices. Ten percent of the electricity usage would be saved. In addition, the time clock would guarantee that the lights are turned "OFF" at the end of the day. Because some offices depend upon a contribution of lighting from an adjacent office, it is doubtful whether the ten percent savings, indicated above, would be achieved.

It is apparent that the lighting system is overdesigned since it initially provides more than twice the illumination requirement. Although it might be more advantageous economically to disconnect one pair of lamps (ballast) in each luminaire and clean more often, this example is concerned only with control systems. An equi-illumination dimming system will reduce the power input to the luminaire to only that which is actually required and might take advantage of the available daylight. A control system should not be based upon utilizing available daylight for at least two reasons. As determined from the estimate of available daylight, the illumination at the window is generally several hundred footcandles. It is probable that some form of window treatment will be used to limit this illumination. In addition, with window shades or curtains open to allow daylight to enter, heat, in the form of radiant energy, will also enter, thus increasing the air conditioning requirements.

An equi-illumination system consisting of five control zones of six luminaires each will be considered. Each zone has two averaging sensors each located between four luminaires. Because of the partitions, the sensors may have different inputs ("see" different amounts of lumen producing elements). It is expected that balancing of sensors to average illumination may be difficult.

6.4.10 Savings Analysis

In order to estimate savings, it is necessary to determine what the luminaire input will be due to the measured illumination. Although the lamps should last for more than

six years, luminaire dirt depreciation after four years should reduce the output light sufficiently to require maximum power input to the ballasts. Luminaires should be relamped and cleaned at least whenever power input is maximum.

It is assumed that input power will vary from 36 percent of maximum (50 fc/160 fc) at the beginning of the project to 100 percent after four years. It is also assumed that the variation is linear with respect to time. The average saving is 32 percent or 4,792 kilowatt-hours per year. At a cost of $0.107 per kilowatt-hour, the annual savings is $513.

6.4.11 System Cost

The cost for a dimming system to be installed at the panelboard and to control a 20 ampere dimming system is approximately $800. Depending upon the size of the control zones, some additional wiring may be required. It is assumed, however, that no additional conduit is necessary because the existing conduit is adequate for the additional conductors. Design cost for this space is assumed to be $500.

6.4.12 Economic Analysis

It is apparent from the System Cost that the Annual Savings is not sufficient to make the five control zone system an economically viable system. The simple payback period is 8.8 years, the Discounted Savings/Investment ratio (SIR) is 1.4 and the E/C ratio is 12.3. In order to improve the above factors, it is necessary to decrease the number of zones (increase the number of luminaires per zone) to decrease the capital cost of dimmers.

In order to increase the E/C ratio to the minimum value of 17, the total project cost must be reduced to $3,270 (55.6/17). Based on design cost and cost per dimmer system, a maximum of three zones (ten luminaires per zone) would meet minimum E/C criteria.

In order to decrease the simple payback period to three years, the total project cost must be reduced to $1,539 or one zone. One zone is not compatible with the equipment specifications because the single dimmer at the given cost can only handle 22 luminaires. At 22 luminaires per dimmer and two zones, the simple payback is 2.80 years.

6.4.13 Recommendations

Based upon the criteria for funding established for these examples, it appears that a dimming system (equi-illumination) may be justified in a retrofit application if the control zones are large and the design cost per zone is reduced by applying the principles to multi-zoned offices.

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MCAS Code 3JA2, Yuma, AZ

NAF CO (Code 18), Midway, Is.; NAF/CO, Lajes, Azores

NAS (Code 18E) Jacksonville, FL; CO (AOT), Whidbey Island, Wa; CO (Code 18.1), Bermuda; CO (Code 18100); CO (Code 18100), Cecil Field, FL; CO (Code 18100), Chase Field, Beeville, Tx; CO (Code 18100), Fallon, NV; CO (Code 1815), Corpus Christi, TX; CO (Code 1824), Lakehurst, NJ; CO (Code 182H), Key West, FL; CO (Code 183U), Miramar, San Diego, Ca; CO (Code 184), Moffett Field, CA; CO (Code 189720), Brunswick, ME; CO (Code 70), Glenview, IL; CO (Code 70), So. Weymouth, MA; CO (Code 71), Willow Grove, PA; CO (Code 721), Belle Chasse LA; Code 18010, Kingsville, TX; Code 18A00, Whiting Fld, Milton, FL; Code 18B00, Lemoore, CA; Code 18D00, Memphis 84, Millington, TN; Code 18E, Oceana, Virginia Beach, VA; Code 70, Atlanta, Marietta GA; Code 70A, Dallas, TX

NATL BUREAU OF STANDARDS Thermal Anal Gp, Wash, DC

NATNAVMEDCEN Code 43, Energy Conserv (PWO) Bethesda, MD

NAVACT CO (Code A171P), London, UK

NAVAIRDEVCEN CO (Code 8323), Warminister, PA

NAVAIRPROPTESTCEN CO (Code PW-3), Trenton NJ

NAVAIRTESTCEN Code PW8L1, Patuxent River, MD

NAVAL HOME PWO, Gulfport, MS

NAVAVIONICFAC Code B/732

NAVCOASTSYSCEN CO (Code 352), Panama City, FL

NAVCOMMAREAMSTRSTA CO (Energy Conserv), Naples, It.

NAVCOMMAREAMSTRSTA Code 41, Norfolk, VA

NAVCOMMSTA CO (Code 20) San Diego, CA; CO (Code 401), Nea Makri, Greece; CO (PWD), Exmouth, Australia; Code 31, Stockton, CA; PWO, Thurso UK

NAVCOMMUNIT CO (Code 50), East Machias, ME

NAVDET OIC (Energy Conserv), Souda, Bay, Crete

NAVEDUTRACEN CO, Code 44, Newport RI

NAVELEXSYSCOM ELEX 1033 Washington, DC

NAVFAC APWO, Pacific Beach, WA; CO (Code 04) Coos Head, Charleston, Or; CO (Code 05) Centerville Beach Fernadale, CA; CO (Code 300), Antigua; CO (Code 50A), Brawdy Wales, UK; CO (Energy Conserv), Big Sur, CA

NAVFACENGCOM Alexandria, VA; Code 03 Alexandria, VA; Code 03T (Essoglou) Alexandria, VA; Code 04 Alexandria VA; Code 05, Alexandria, VA; Code 08, Alexandria VA; Code 09M54, Tech Lib, Alexandria, VA; Code 11, Alexandria, VA; Code 111 Alexandria, VA; Code 1113, Alexandria, VA; Code 111B (Hanneman), Alexandria, VA

NAVFACENGCOM - CHES DIV. Code 04, Wash, DC; Code 05, Wash, DC; Code 10/11, Washington, DC; Code 112, Wash, DC; Library, Washington, D.C.

NAVFACENGCOM - LANT DIV. Code 04 Norfolk VA; Code 05, Norfolk, VA; Code 11, Norfolk, VA; Code 1112, Norfolk, VA; Library, Norfolk, VA

NAVFACENGCOM - NORTH DIV. Code 04 Philadelphia, PA; Code 04AL, Philadelphia PA; Code 05, Phila, PA; Code 11, Phila PA; Code 111 Philadelphia, PA

NAVFACENGCOM - PAC DIV. Code 04 Pearl Harbor HI; Code 05, Pearl Harbor, HI; Code 11 Pearl Harbor
 HI; Code 111, Pearl Harbor, HI; Code 402, RDT&E, Pearl Harbor HI; Library, Pearl Harbor, HI
NAVFACENGCOM - SOUTH DIV. Code 04, Charleston, SC; Code 05, Charleston, SC; Code 11, Charleston,
 SC; Code 1112, Charleston, SC; Library, Charleston, SC
NAVFACENGCOM - WEST DIV. Code 04, San Bruno, CA; Code 05, San Bruno, CA; Code 11 San Bruno,
 CA; Library, San Bruno, CA; RDT&ELO San Bruno, CA
NAVFUEL DEP OIC (Energy Conserv), JAX, Fl
NAVHOSP CO Long Beach, CA; Code 310, Portsmouth, VA; Code 93, Portsmouth, VA
NAVOBSY Code 67, Washington DC
NAVOCEANSYSCEN Commander (Code 411), San Diego, CA
NAVORDFAC CO (Code 66), Sasebo, Japan
NAVORDSTA CO (Code 0931), Louisville, KY; CO (Code 1042) Louisville, KY; Code 092, Indian Head, MD
NAVORDSYSCOM Code SPL-631
NAVPGSCOL Code 43B, Monterey, CA
NAVPHIBASE PWO Norfolk, VA
NAVPLANTREP Hercules Inc., Magna, UT
NAVRESREDCOM (13), Code 07, Great Lakes, IL; Commander (Code 072), San Francisco, CA
NAVSCOLCECOFF C35 Port Hueneme, CA
NAVSCSCOL CO (Code 50), Athens, GA
NAVSEASYSCOM PMS 396.33 Washington DC
NAVSECGRUACT CO (Code 30), Puerto Rico; CO (Code 40B), Edzell, Scotland; CO (Code N60),
 Homestead, FL; CO (Energy Conserv), Sonoma, CA; CO (Energy Conserv.) Winter Harbor, ME; Code 40,
 Chesapeake, VA; PWD, ADAK, AK
NAVSECGRUCOM Energy Conserv., Washington DC
NAVSECSTA Code 540, Washington DC
NAVSHIPYD Code 402.4, Philadelphia PA; Code 405, Vallejo, CA; Code 440.8, Bremerton, WA; Commander
 (Code 406), Portsmouth, NH; PWD (Code 450.44), Enrgy Consv Engr, Charleston, SC
NAVSTA (Code 50A) '' 'han, Panama Canal; CO (Code 18410), Mayport, FL; CO (Code 4'' Grmo, Cuba;
 CO (Code 52), Brook n NY; CO (PWD), Rota, Spain; Code 0D3, San Diego, CA
NAS Energy Conserv, Adak, AK
NAVSUBASE Code 803, Groton,CT; PWO Bangor, Bremerton, WA
NAVSUPPACT (Code PW7) Naples, Italy; CO (Code 413), Seattle, WA; CO (Code 81), Mare Island, Vallejo,
 CA; CO (Code N52), New Orleans, LA; PWD, Holy Loch UK
NAVSUPPFAC CO (Energy Conserv) Diego Garcia I; Code 02, Thurmont, MD
NAVSUPPO CO (APWO), La Maddalena, Italy
NAVSURFWPNCEN Code W0-5, Dahlgren VA
NAVTELCOMMCOM Code 05, Washington DC
NAVUSEAWARENGSTA CO (Code 073E2), Keyport, WA
NAVWPNCEN Commander (Code 2635), China Lake, CA
NAVWPNSTA CO (Code 09221), Concord, CA; CO (Energy Conserv) Yorktown, VA; CO (Energy Conserv),
 Colts Neck, NJ; Code 0911, Seal Beach CA
NAVWPNSUPPCEN CO (Code 092E), Crane, IN
SUBASE Energy Conserv, Kings Bay, GA
NCBC CO (Code 50), Port Hueneme, CA, CO (Energy Conserv), Davisville, RI
NOAA Library Rockville, MD
NRL PWO Code 2530.1, Washington, DC
NSC CO (Code 46A) San Diego, CA, CO (Code 70A), Puget Sound, WA
NSD CO (Code 50E)
NAVADMINCOM Code NAC50E, Orlando, Fl
NUSC DET CO (Code 5204), Newport, RI
ONR CO (Code 701) Pasadena, CA, Code ONT-07E, Arlington, VA
PACMISRANFAC Code 7032, HI Area, Kekaha, HI
PMTC Code 6200.3, Point Mugu, CA
PWC CO (Code 100F), San Diego, CA, CO (Code 100E3), Oakland, CA; CO (Code 30), Pearl Harbor, HI; CO
 (Code 610) Pensacola, FL, CO (Code 613), San Diego, CA; CO Code 100E, Oakland, CA; CO, NAS
 Pensacola FL, Code 100A, Great Lakes, IL, Code 101 (Library), Oakland, CA; Code 116, Yokosuka, JA;
 Code 123 C, San Diego, CA, Code 153, Guam, Mariana Islands; Code 154 (Library), Great Lakes, IL; Code
 600A Norfolk, VA, Code 610, Subic Bay RP, Library, Norfolk, VA; Library, Pearl Harbor, HI; Library,
 Pensacola FL, Library, Subic Bay, R P.; Library, Yokosuka JA
SPCC Code 763, Mechanicsburg, PA
SUPSHIP ADMINO, San Francisco, CA; Code 901
USNA Code 170, Annapolis, MD, Director of Research, Annapolis, MD
BALL STATE UNIVERSITY R Meden, Muncie, IN
FRANKLIN INSTITUTE M Padusis, Philadelphia PA
LAWRENCE BERK LAB Window & Lighting Prog, Berkeley, cA

LOS ALAMOS SCI LAB Solar Energy Gp. Los Alamos, NM
MIT Cambridge MA (Rm 10-500, Tech. Reports, Engr. Lib.)
UNIVERSITY OF WASHINGTON Insti. for Envir. Studies
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